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Keller et al.

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(45) **Date of Patent: Jun. 9, 2020**

(54) **METHODS, DEVICES, AND SYSTEMS FOR CREATING HAPTIC STIMULATIONS AND TRACKING MOTION OF A USER**

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(51) **Int. Cl.**
G06F 3/01 (2006.01)
G06F 1/16 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G06F 3/016*** (2013.01); ***G06F 1/163*** (2013.01); ***G06F 3/011*** (2013.01); ***G06F 3/014*** (2013.01);
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CPC G06F 3/016; G06F 3/011; G06F 3/014; G06F 3/015; G06F 3/017; G06F 1/163; G06K 19/07762; G06T 19/006
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

9,797,691 B1	10/2017	Hunn et al.
2014/0125571 A1	5/2014	Um et al.

(Continued)

FOREIGN PATENT DOCUMENTS

WO	WO2015-102464 A1	7/2015
WO	WO2015-127116 A1	8/2015
WO	WO2015-199898 A1	12/2015

OTHER PUBLICATIONS

Da-Chen Pang et al., A Transparent Capacitive Micromachined Ultrasonic Transducer (CMUT) Array for Finger Hover-Sensing Dial Pads, 2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers), Kaohsiung, Taiwan: IEEE, Jun. 18-22, 2017, pp. 2171-2174, 4 pgs.

(Continued)

Primary Examiner — Peter D McLoone
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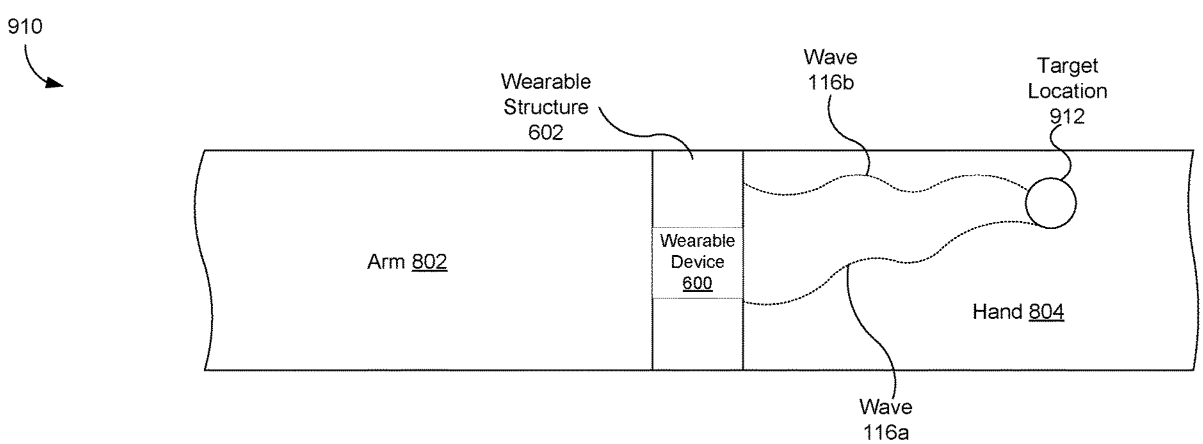
(57) **ABSTRACT**

A method of creating haptic stimulations and anatomical information includes a wearable device including a plurality of transducers that can each generate one or more waves. The method includes activating one or more first transducers of the plurality of transducers based on an instruction
(Continued)



received from a remote device. Waves generated by the activated one or more first transducers provide a haptic stimulation. The method further includes activating one or more second transducers of the plurality of transducers. Waves generated by the activated one or more second transducers provide anatomical information of a user of the wearable device when the waves are received by one or more transducers of the plurality of transducers.

20 Claims, 19 Drawing Sheets

Related U.S. Application Data

filed on Mar. 23, 2018, provisional application No. 62/636,699, filed on Feb. 28, 2018, provisional application No. 62/614,790, filed on Jan. 8, 2018.

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G06K 19/077 (2006.01)
G06T 19/00 (2011.01)

(52) **U.S. Cl.**
CPC ***G06F 3/015*** (2013.01); ***G06F 3/017*** (2013.01); ***G06K 19/07762*** (2013.01); ***G06T 19/006*** (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2016/0019762 A1 1/2016 Levesque et al.
2016/0100034 A1 4/2016 Miller
2016/0357261 A1 12/2016 Bristol et al.
2017/0097753 A1 4/2017 Bailey et al.
2017/0102771 A1* 4/2017 Lei G06F 3/0436
2017/0115733 A1 4/2017 Du
2017/0123487 A1* 5/2017 Hazra G06F 3/015
2017/0220005 A1 8/2017 Han et al.

OTHER PUBLICATIONS

FaceBook Technologies, LLC, International Search Report and Written Opinion, PCT/US2019/012697, dated Apr. 29, 2019, 10 pgs.
FaceBook Technologies, LLC, International Search Report and Written Opinion, PCT/US2019/012702, dated Apr. 29, 2019, 11 pgs.
FaceBook Technologies, LLC, International Search Report and Written Opinion, PCT/US2019/012718, dated May 3, 2019, 10 pgs.
FaceBook Technologies, LLC, International Search Report and Written Opinion, PCT/US2019/012721, dated Apr. 29, 2019, 10 pgs.
Zhang, "SkinTrack: Using the Body as an Electrical Waveguide for Continuous Finger Tracking on the Skin," © 2016 ACM, ISBN978-1-4503-3362-7/16/05, 13 pgs.

* cited by examiner

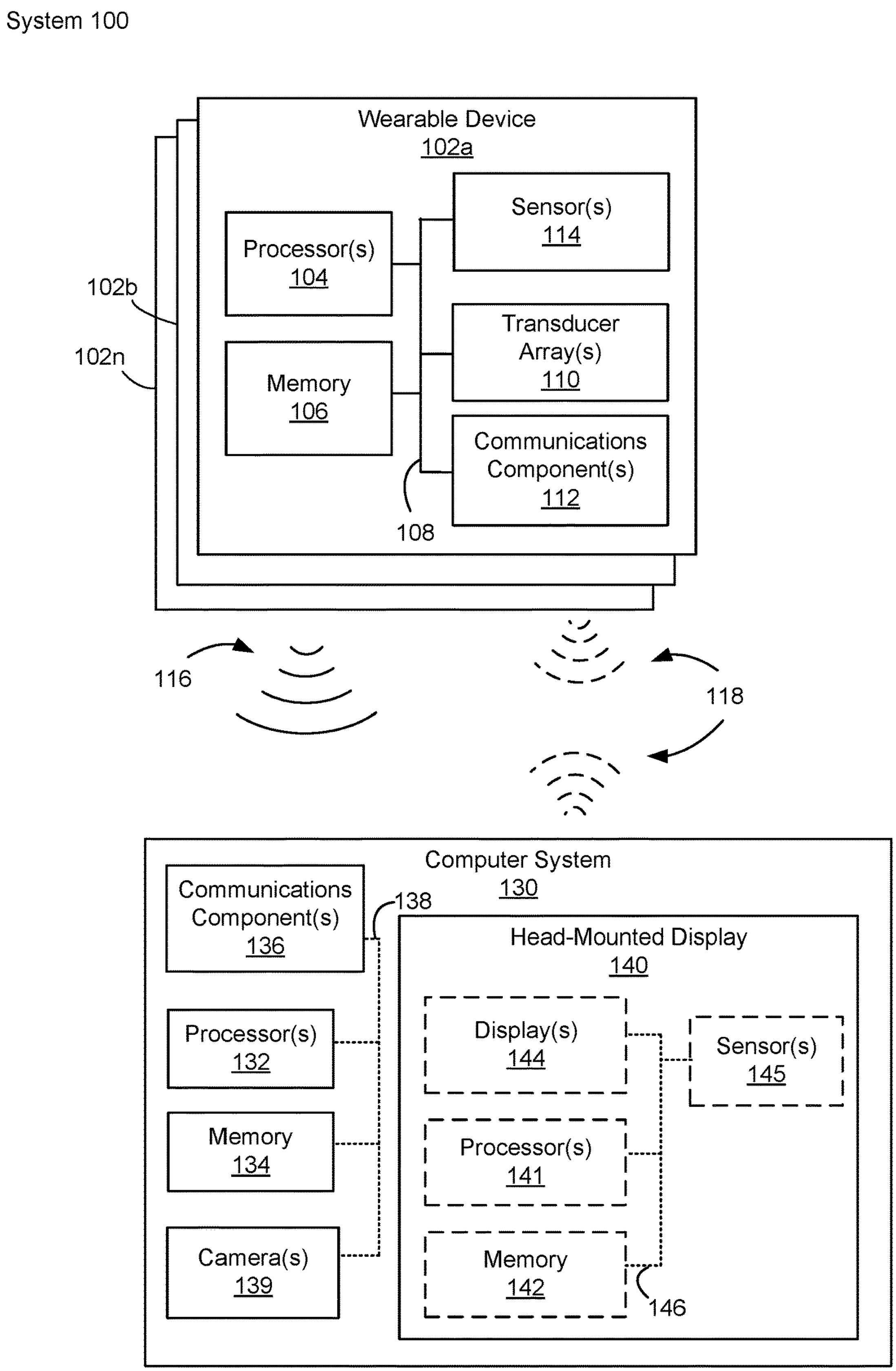

System 100
Wearable Device
102a
Processor(s)
104
Memory
106
Sensor(s)
114
Transducer
Array(s)
110
Communications
Component(s)
112
108
102b
102n
116
118
Computer System
130
Communications
Component(s)
136
138
Head-Mounted Display
140
Processor(s)
132
Memory
134
Camera(s)
139
Display(s)
144
Sensor(s)
145
Processor(s)
141
Memory
142
146

Figure 1

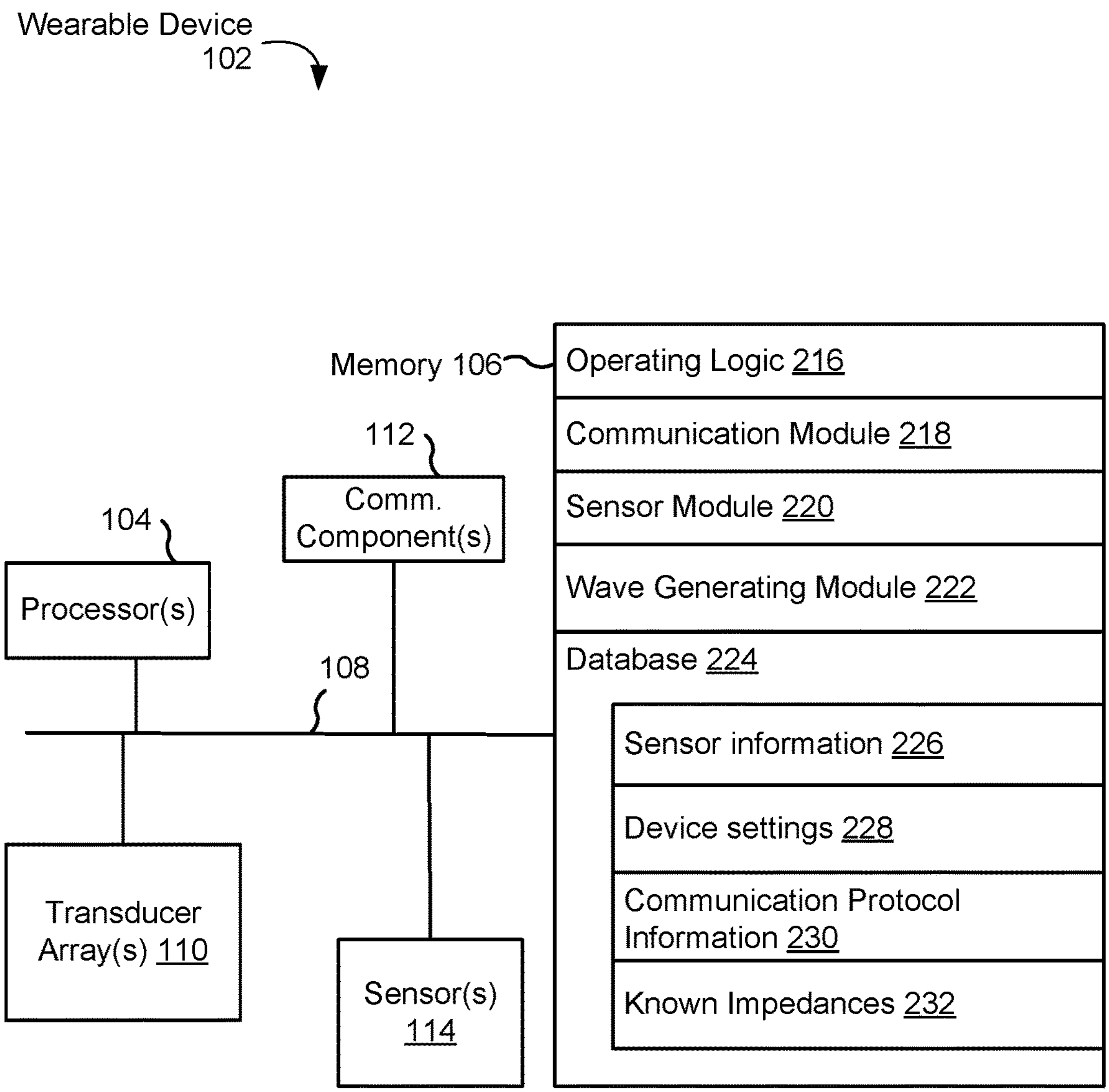

Wearable Device
102
Memory 106
Operating Logic 216
Communication Module 218
Sensor Module 220
Wave Generating Module 222
Database 224
Sensor information 226
Device settings 228
Communication Protocol Information 230
Known Impedances 232
112
Comm. Component(s)
104
Processor(s)
108
Transducer Array(s) 110
Sensor(s) 114

Figure 2

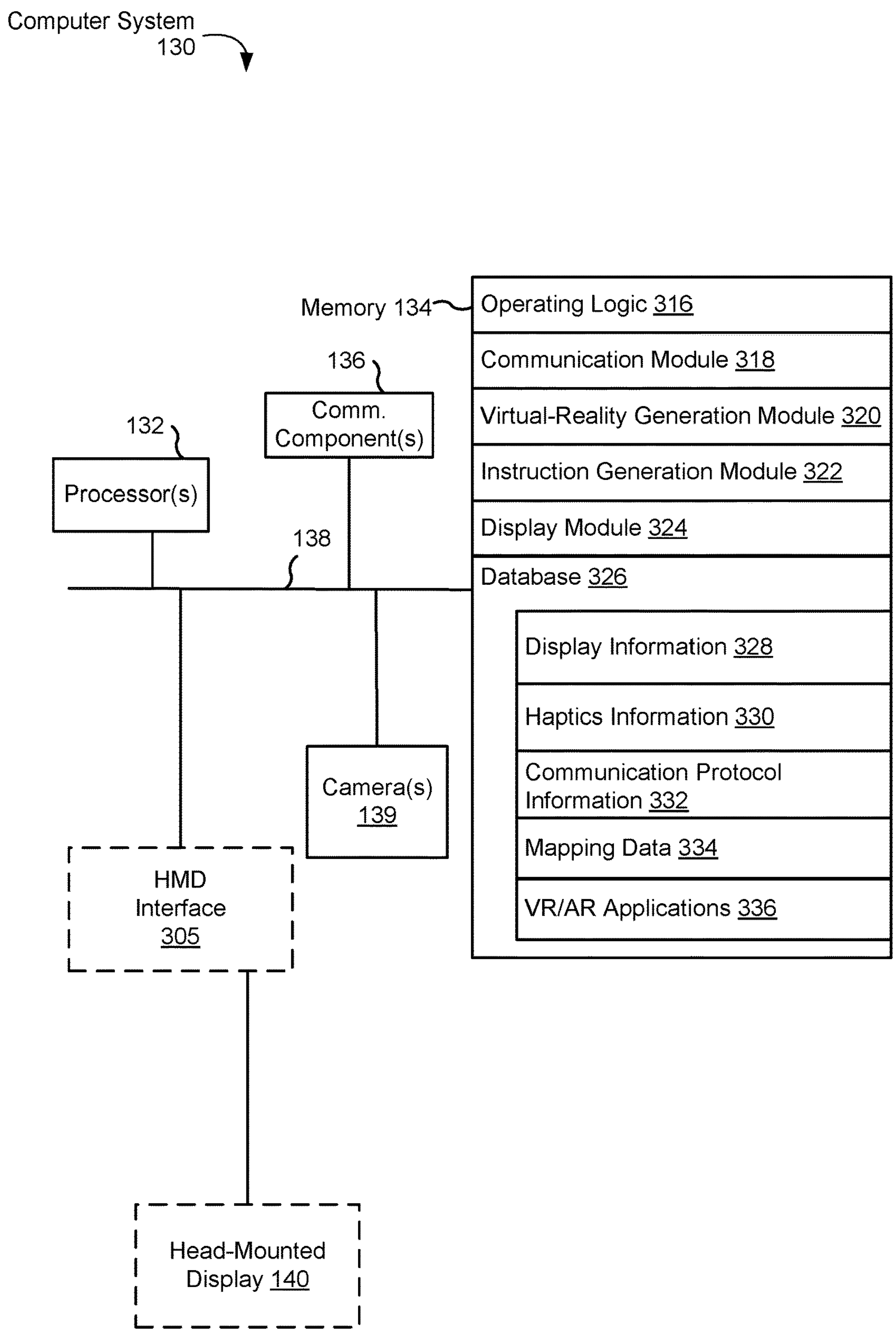

Computer System
130
Memory 134
Operating Logic 316
Communication Module 318
Virtual-Reality Generation Module 320
Instruction Generation Module 322
Display Module 324
Database 326
Display Information 328
Haptics Information 330
Communication Protocol Information 332
Mapping Data 334
VR/AR Applications 336
136
Comm. Component(s)
132
Processor(s)
138
Camera(s)
139
HMD Interface
305
Head-Mounted Display 140

Figure 3

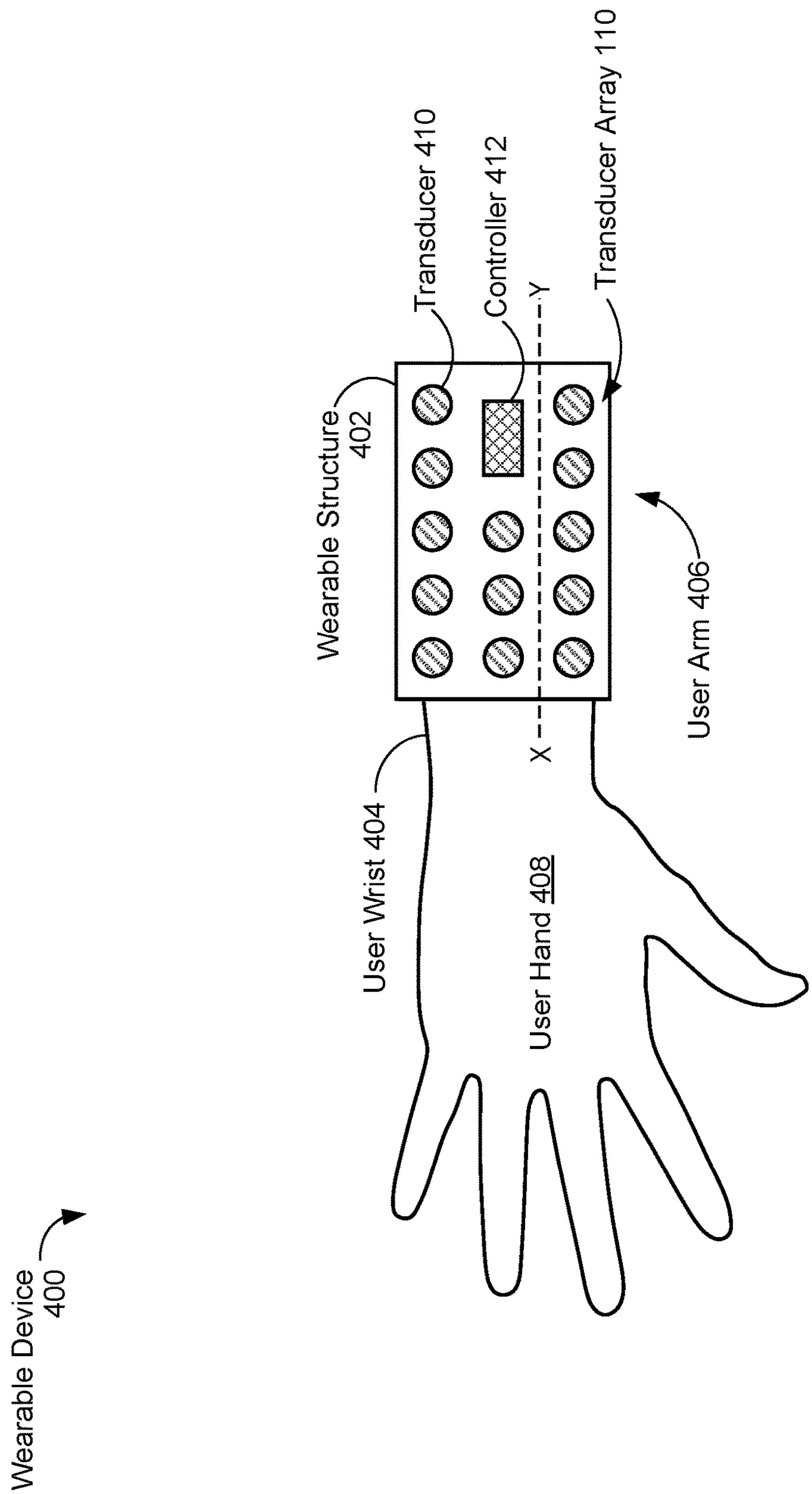

Transducer 410
Controller 412
Transducer Array 110
Y
X
Wearable Structure 402
User Arm 406
User Wrist 404
User Hand 408
Wearable Device 400

Figure 4

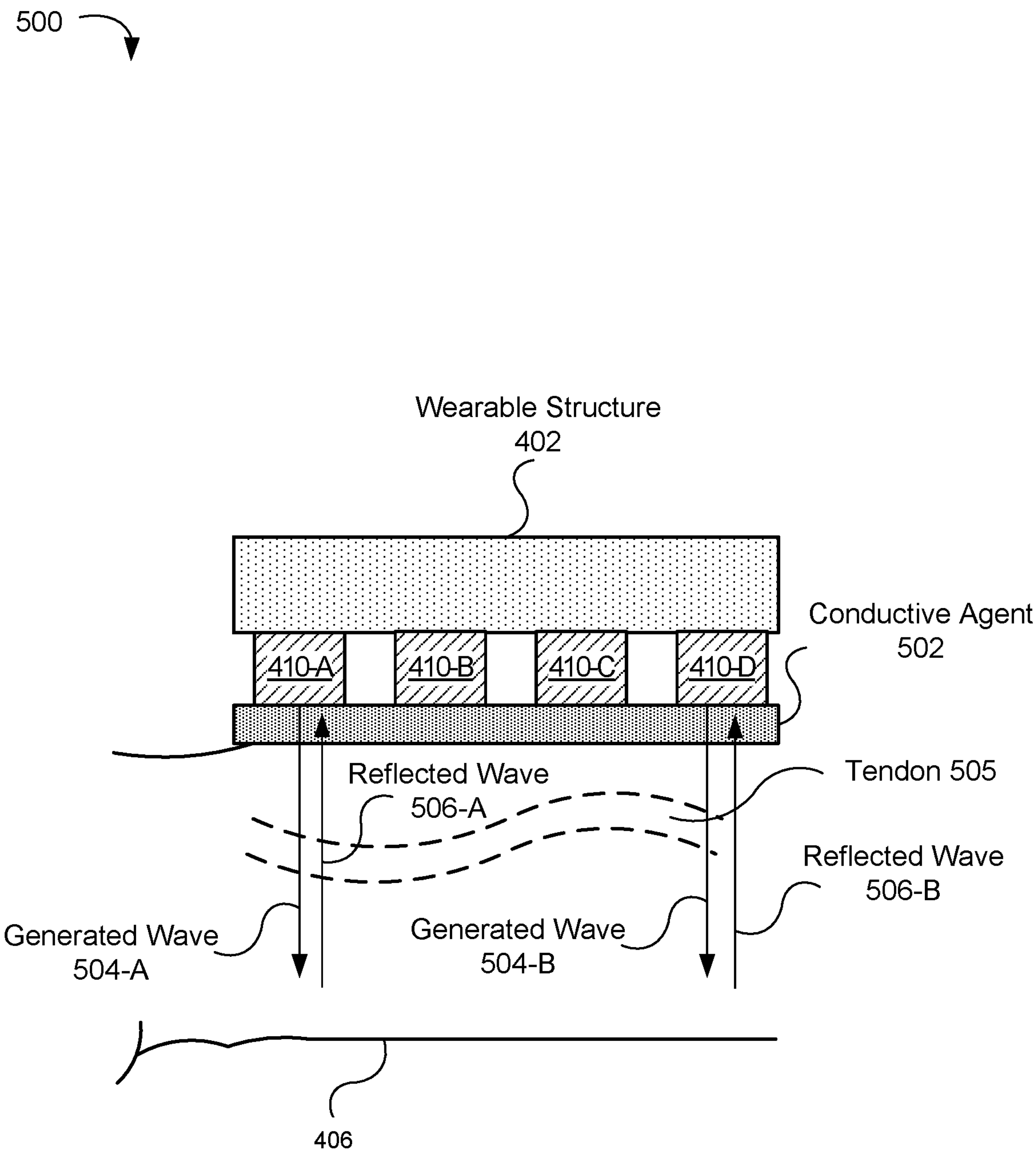

500
Wearable Structure
402
Conductive Agent
502
410-A
410-B
410-C
410-D
Reflected Wave
506-A
Tendon 505
Reflected Wave
506-B
Generated Wave
504-A
Generated Wave
504-B
406

Figure 5A

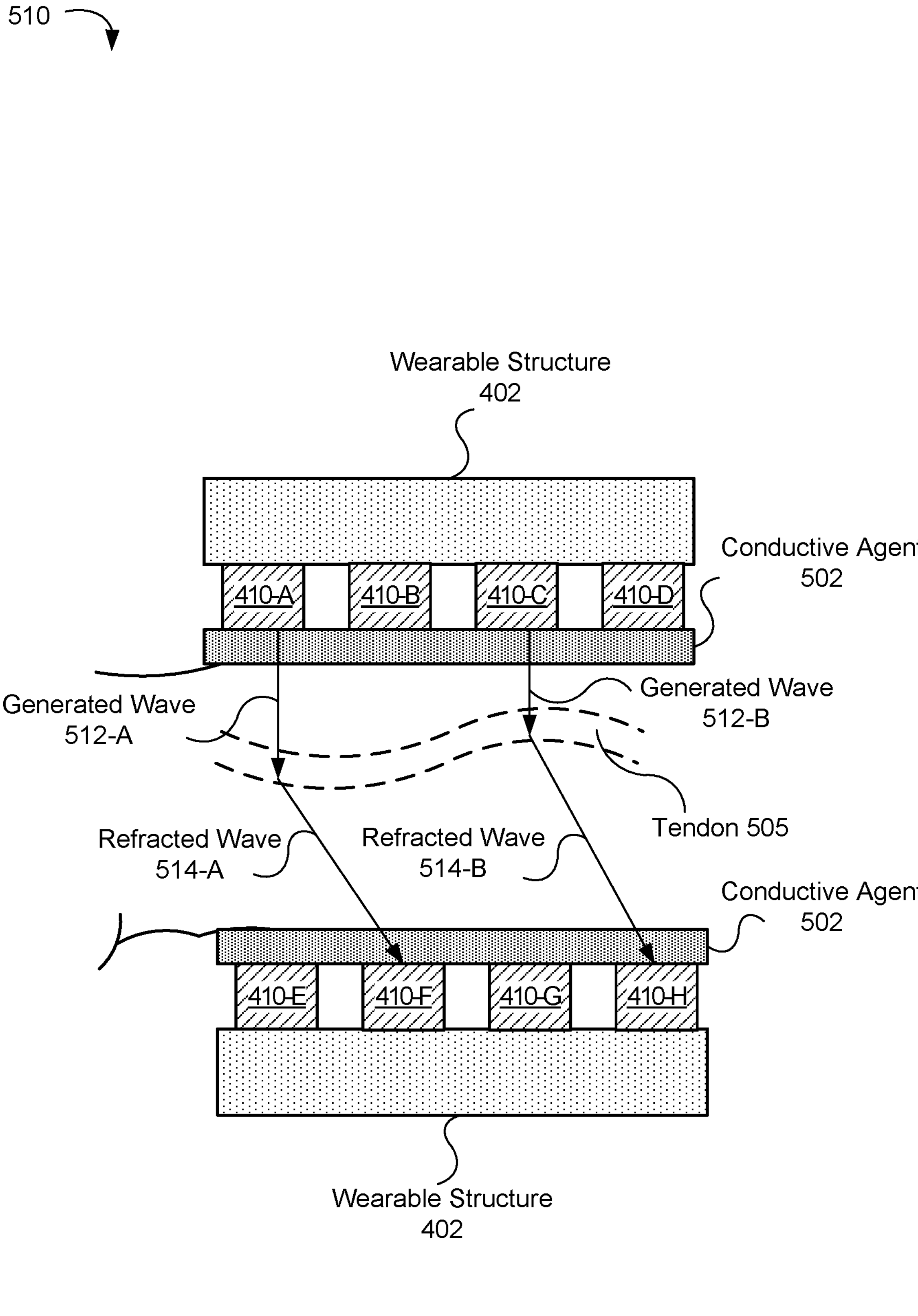

510
Wearable Structure
402
Conductive Agent
502
410-A
410-B
410-C
410-D
Generated Wave
512-A
Generated Wave
512-B
Tendon 505
Refracted Wave
514-A
Refracted Wave
514-B
Conductive Agent
502
410-E
410-F
410-G
410-H
Wearable Structure
402

Figure 5B

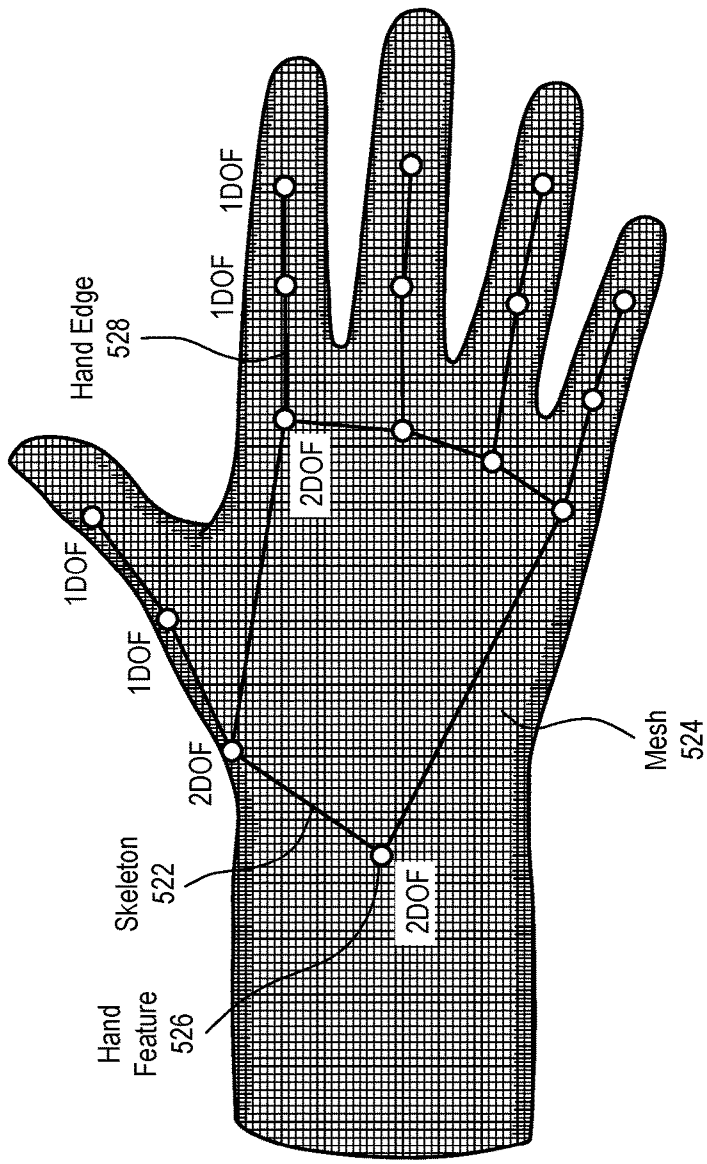


Figure 5C

520

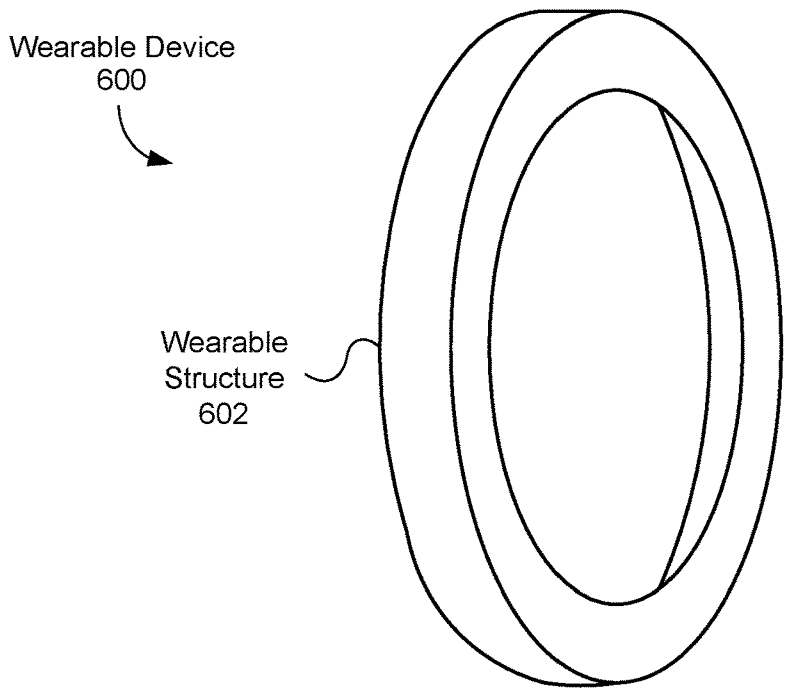


Figure 6A

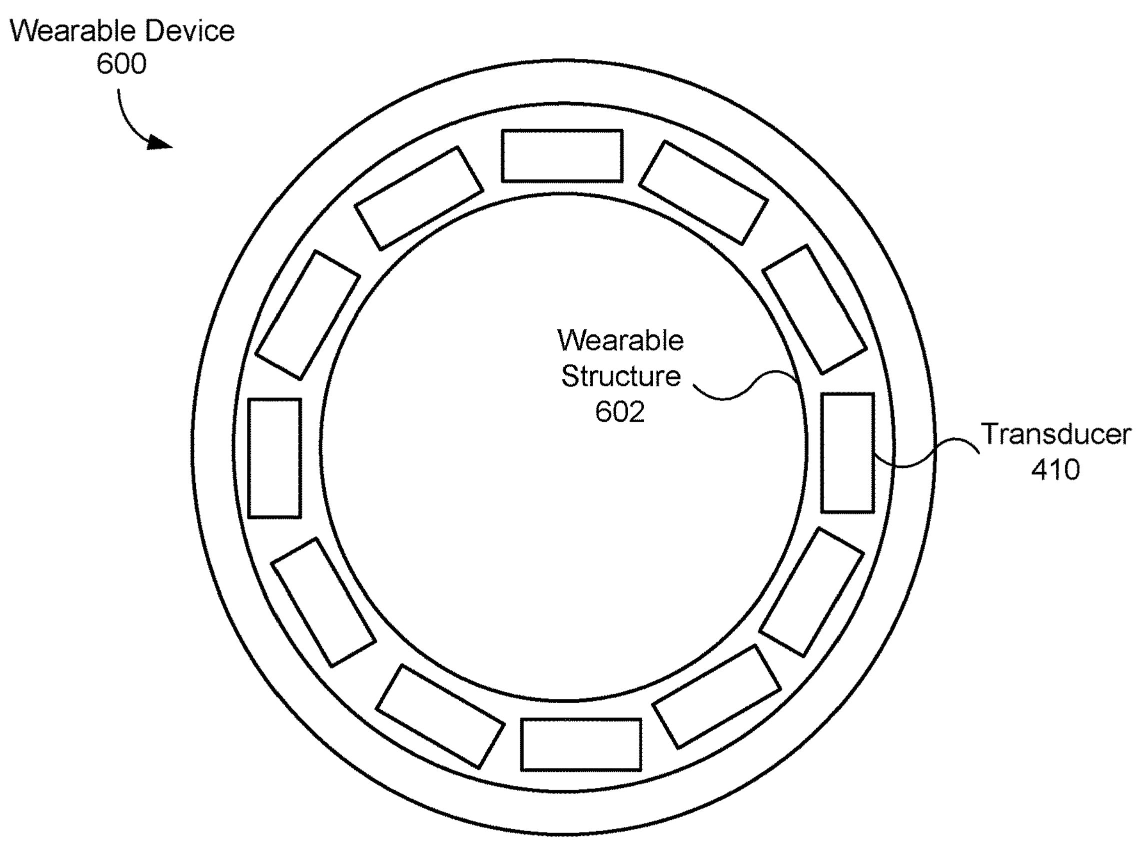


Figure 6B

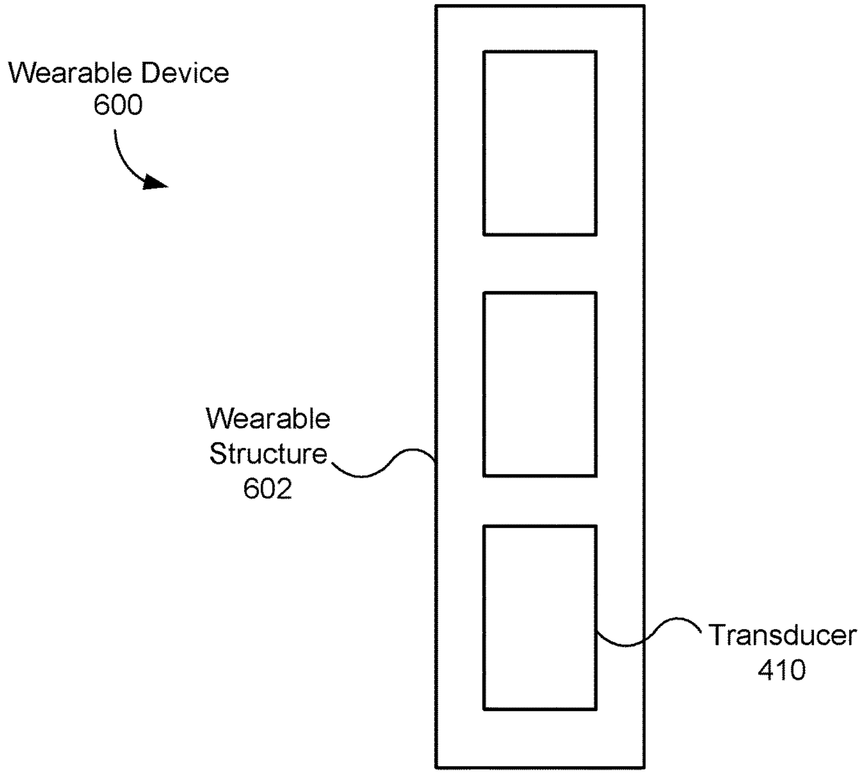


Figure 7A

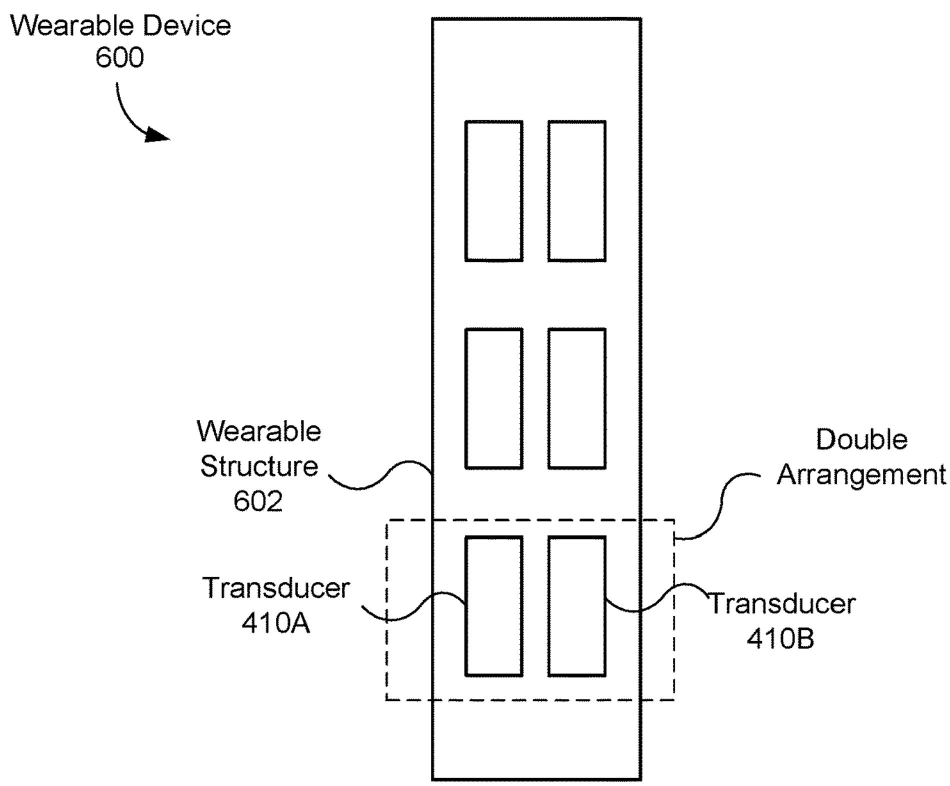


Figure 7B

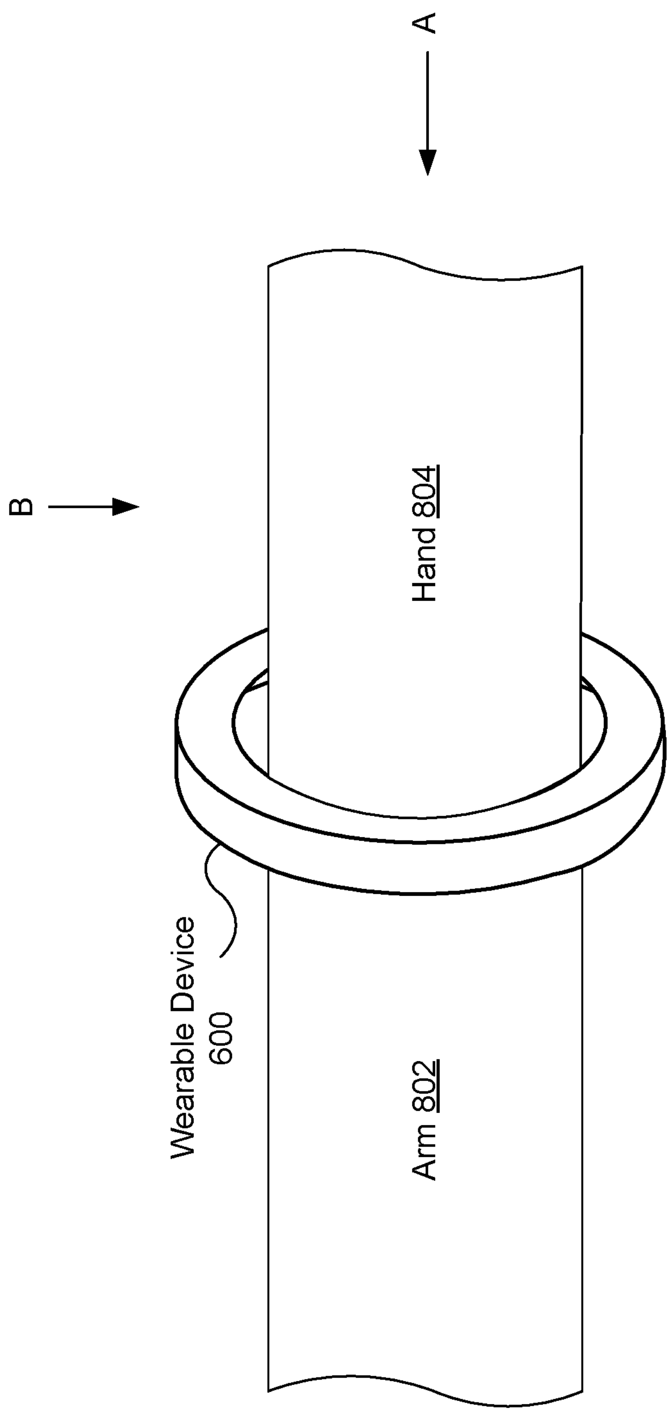


Figure 8

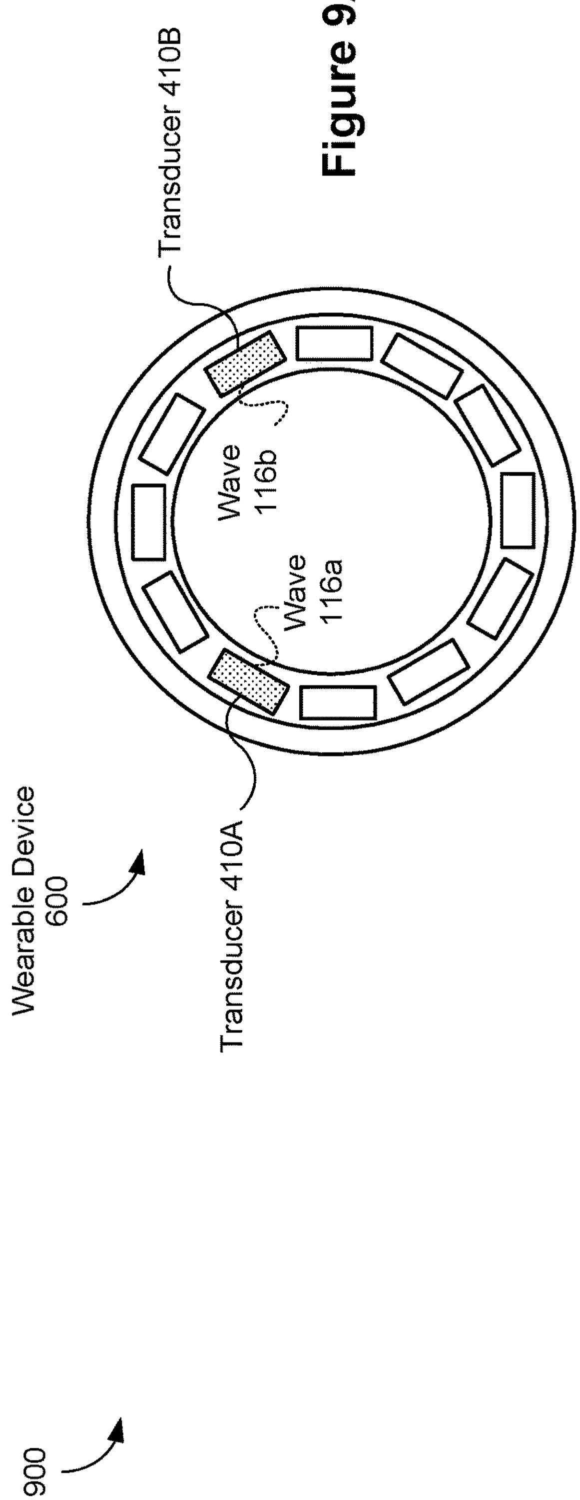


Figure 9A

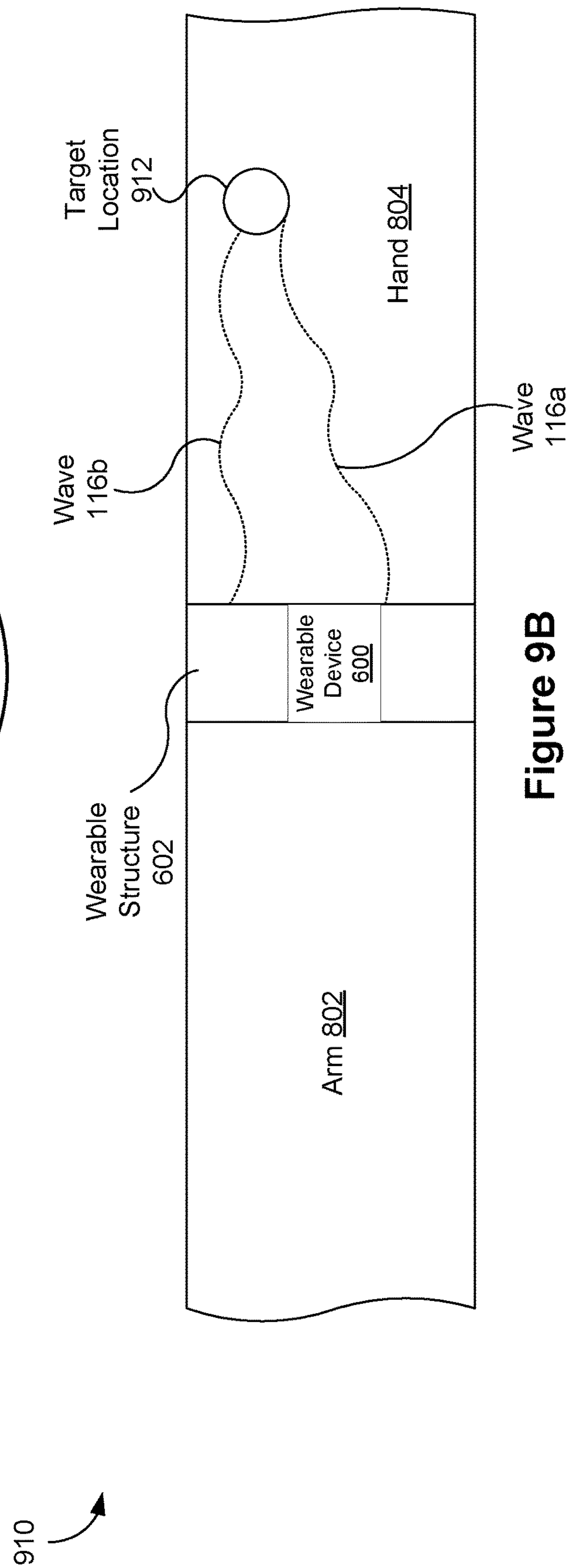


Figure 9B

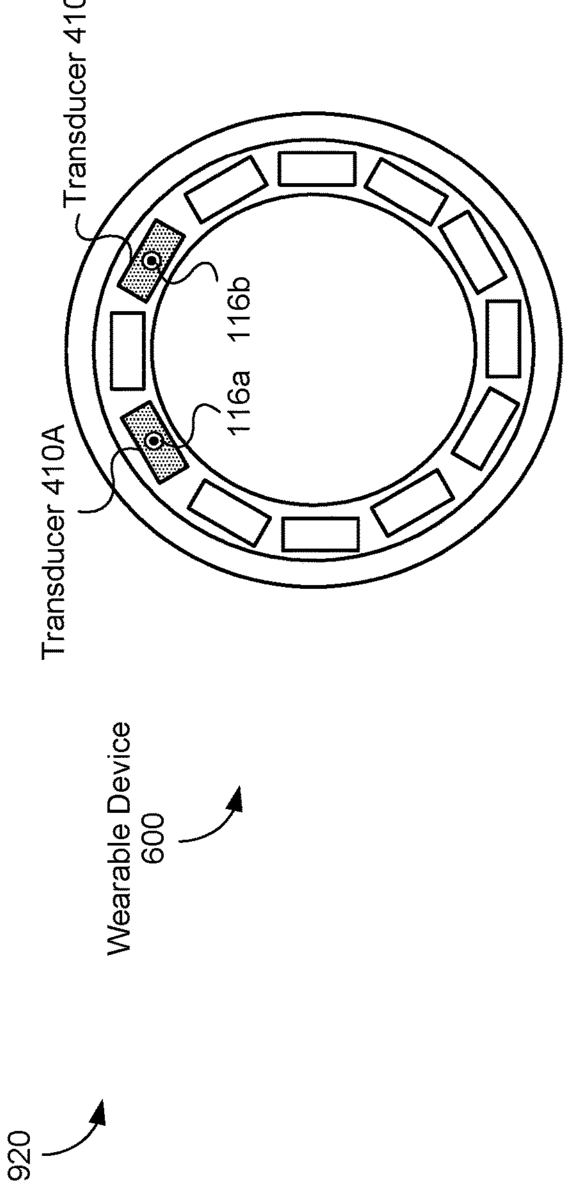


Figure 9C

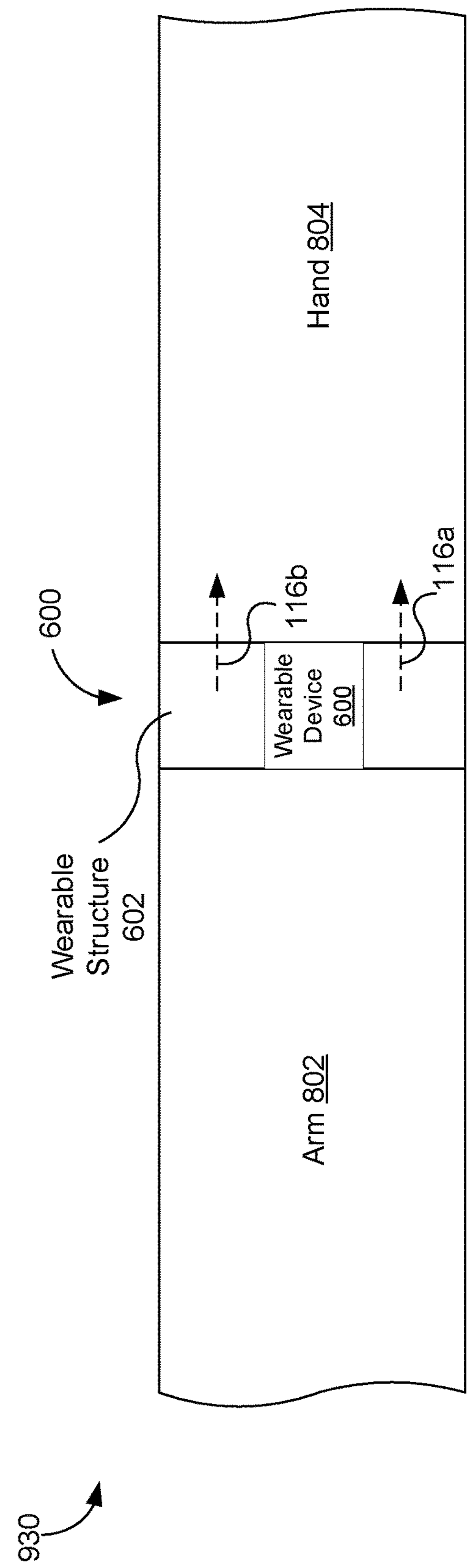


Figure 9D

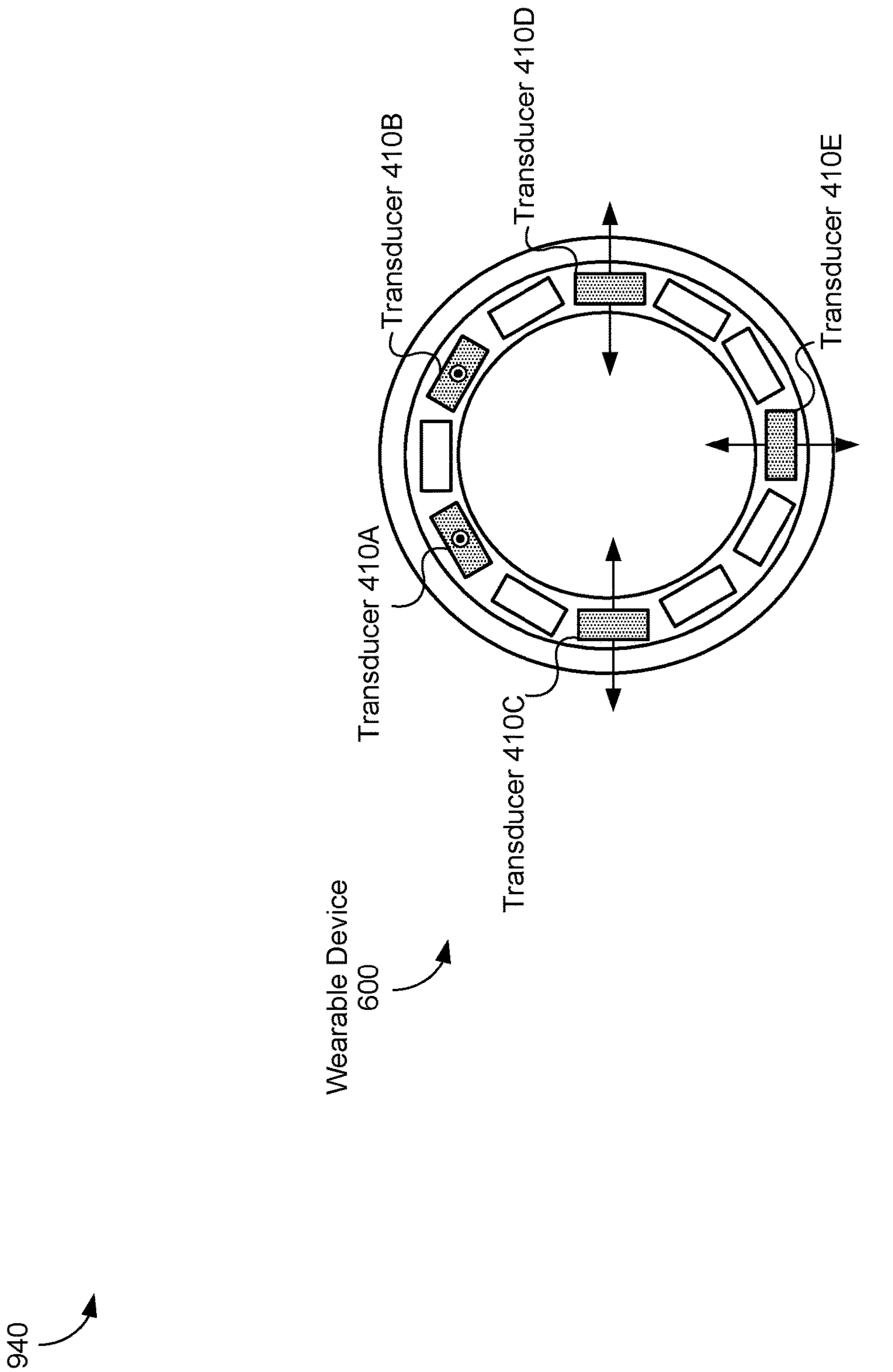

940
Wearable Device
600
Transducer 410A
Transducer 410B
Transducer 410C
Transducer 410D
Transducer 410E

Figure 9E

1000

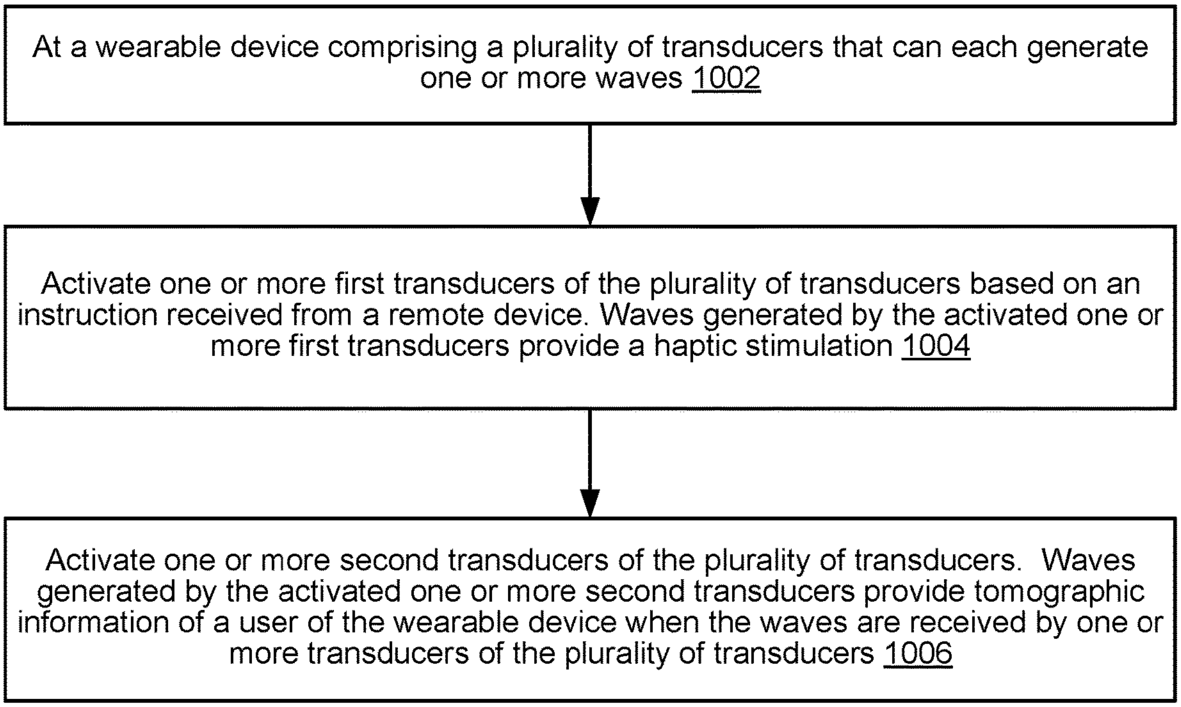


Figure 10

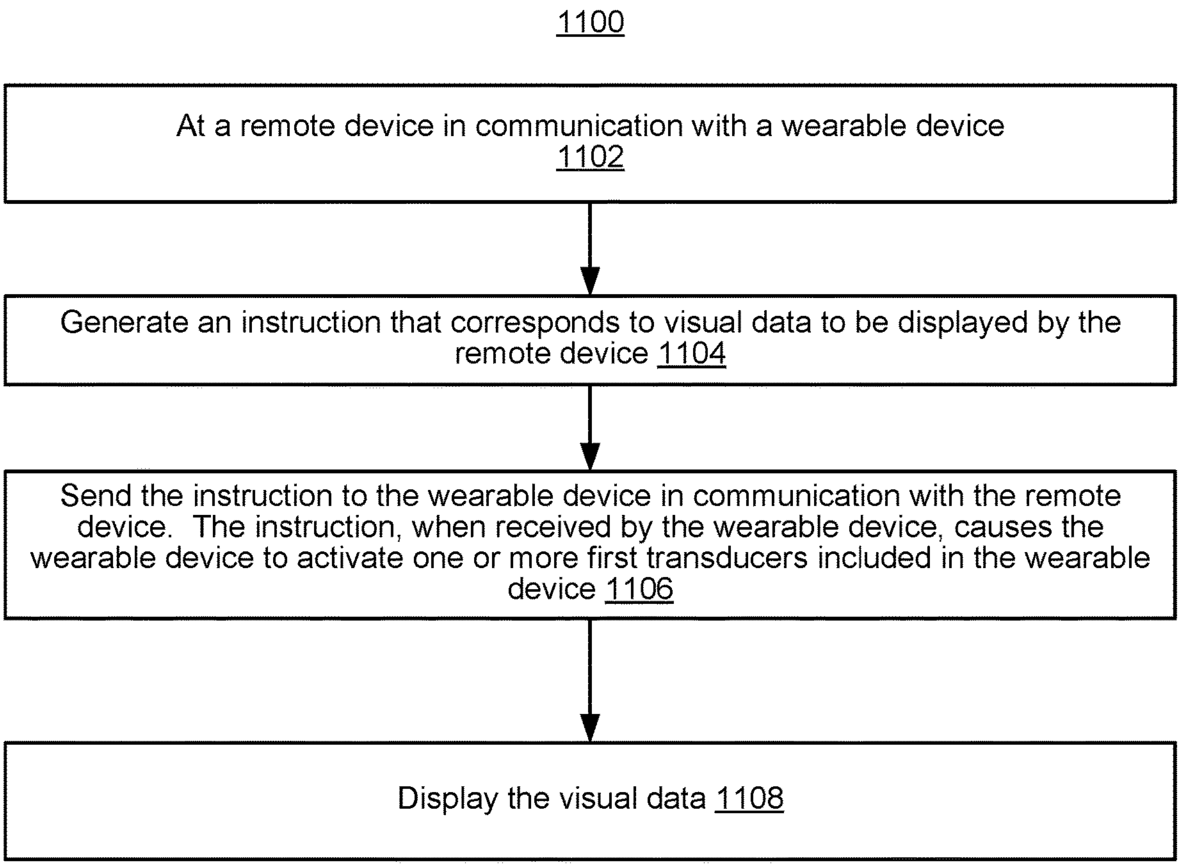

1100
At a remote device in communication with a wearable device 1102
Generate an instruction that corresponds to visual data to be displayed by the remote device 1104
Send the instruction to the wearable device in communication with the remote device. The instruction, when received by the wearable device, causes the wearable device to activate one or more first transducers included in the wearable device 1106
Display the visual data 1108

Figure 11

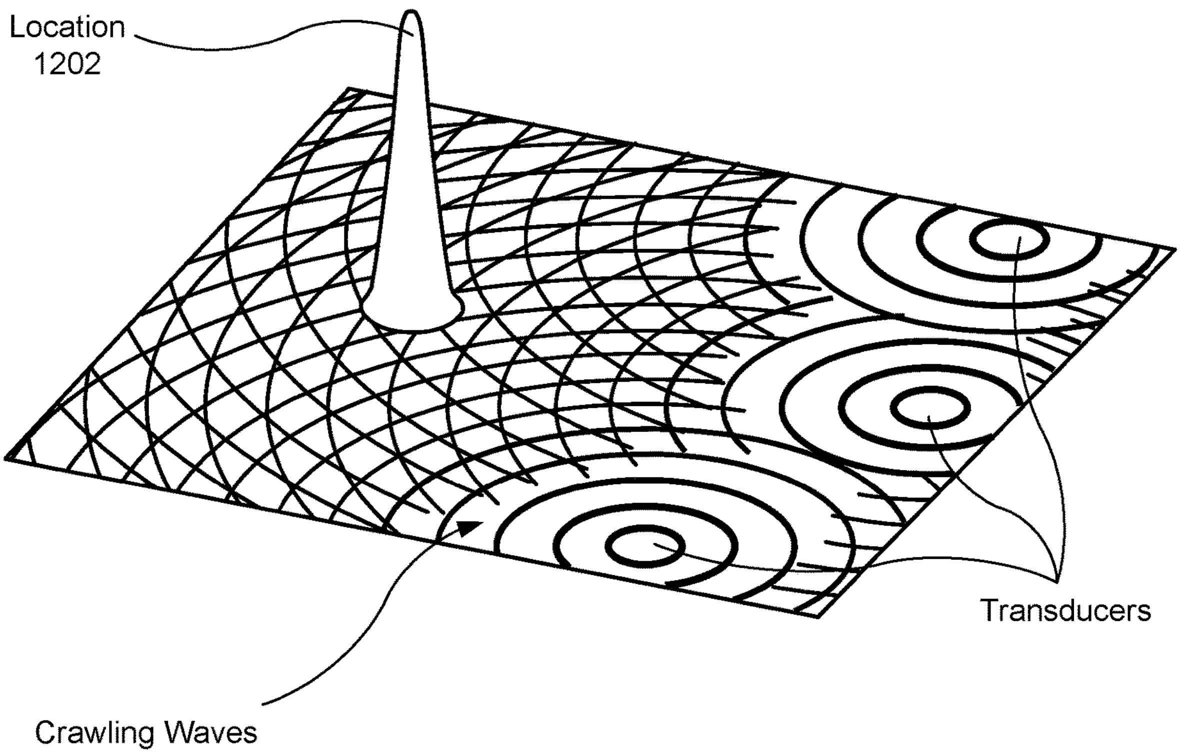


Figure 12

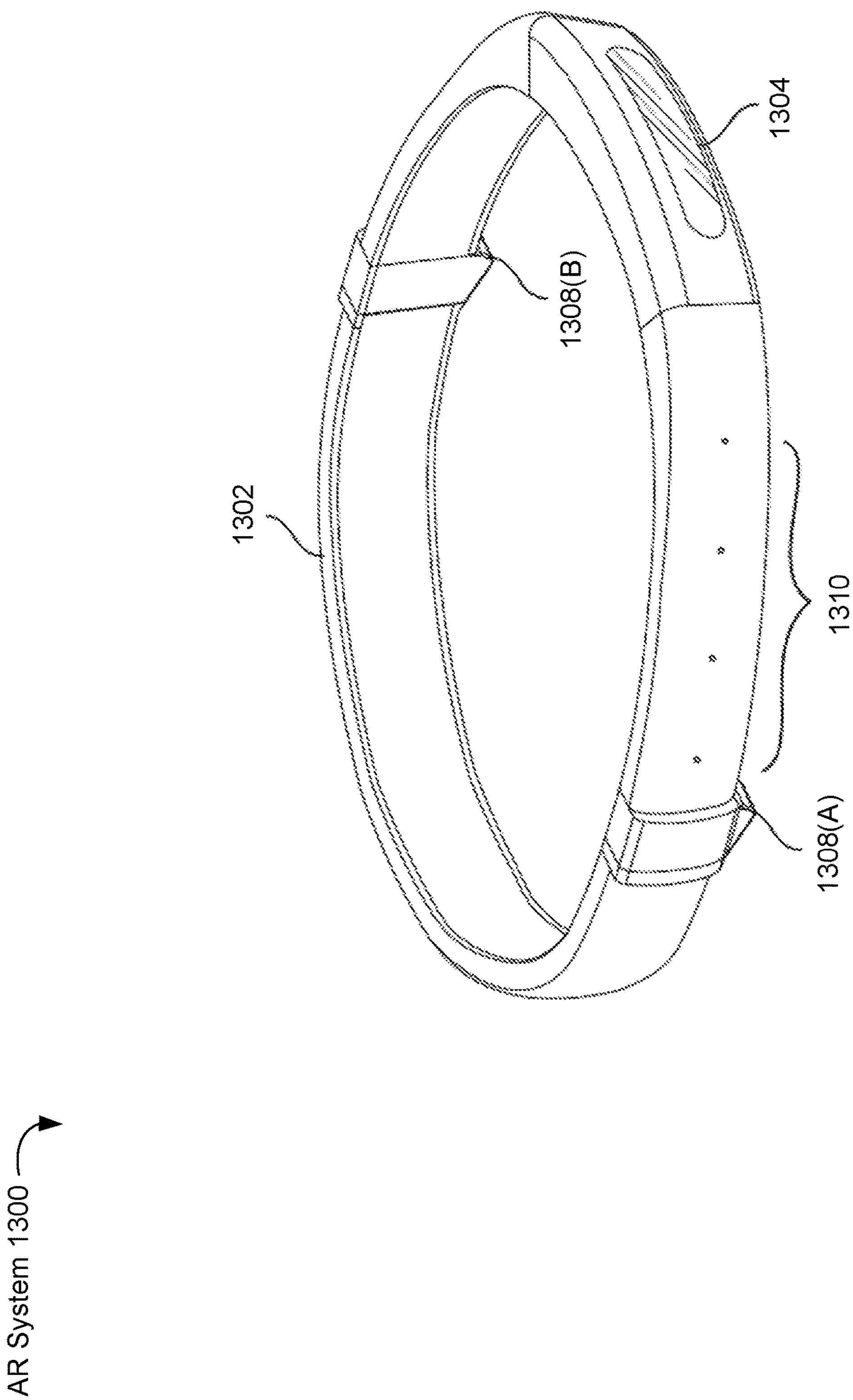
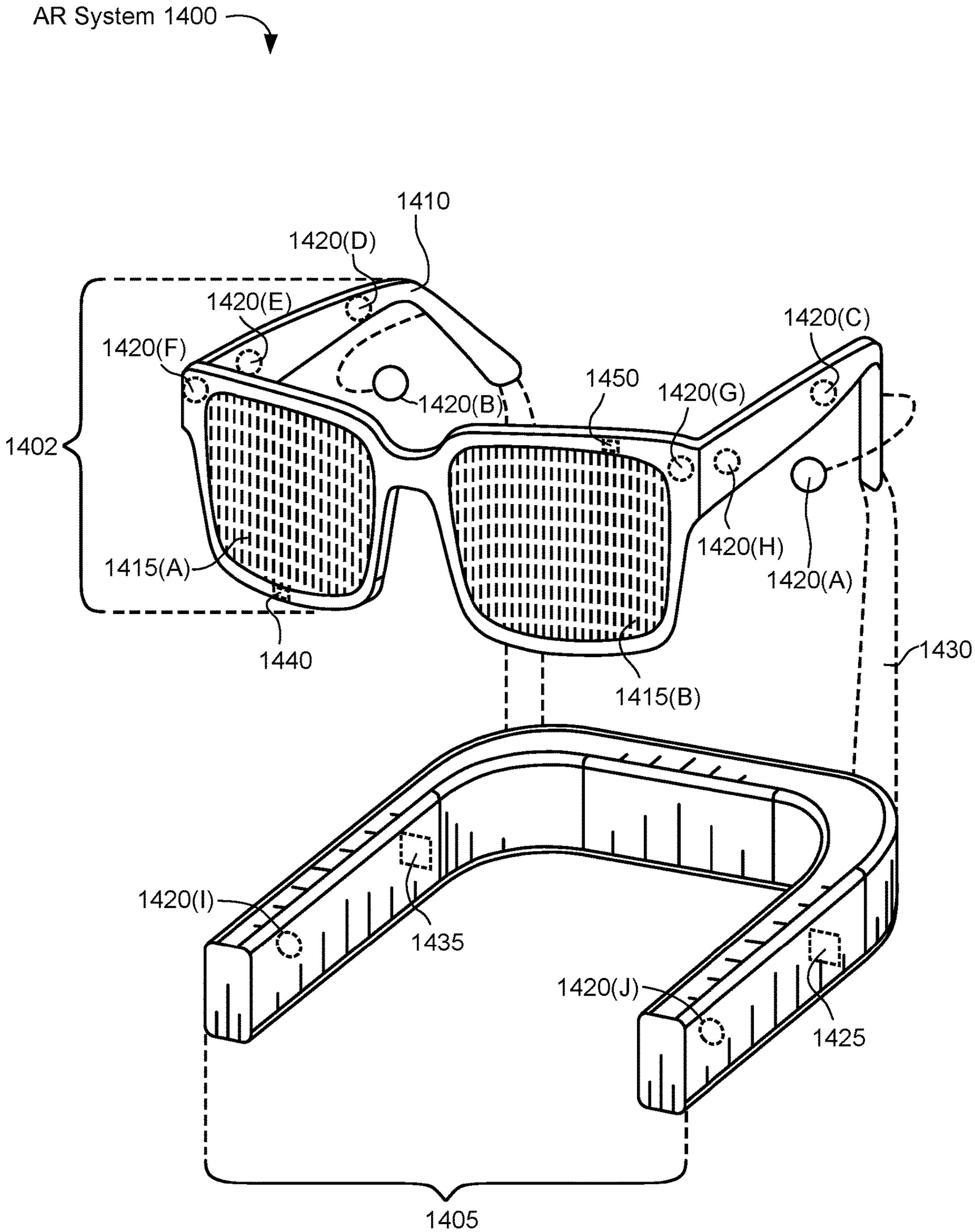


Figure 13



AR System 1400
1410
1420(D)
1420(E)
1420(F)
1420(B)
1450
1420(G)
1420(C)
1402
1415(A)
1440
1420(H)
1420(A)
1430
1415(B)
1420(I)
1435
1420(J)
1425
1405

Figure 14

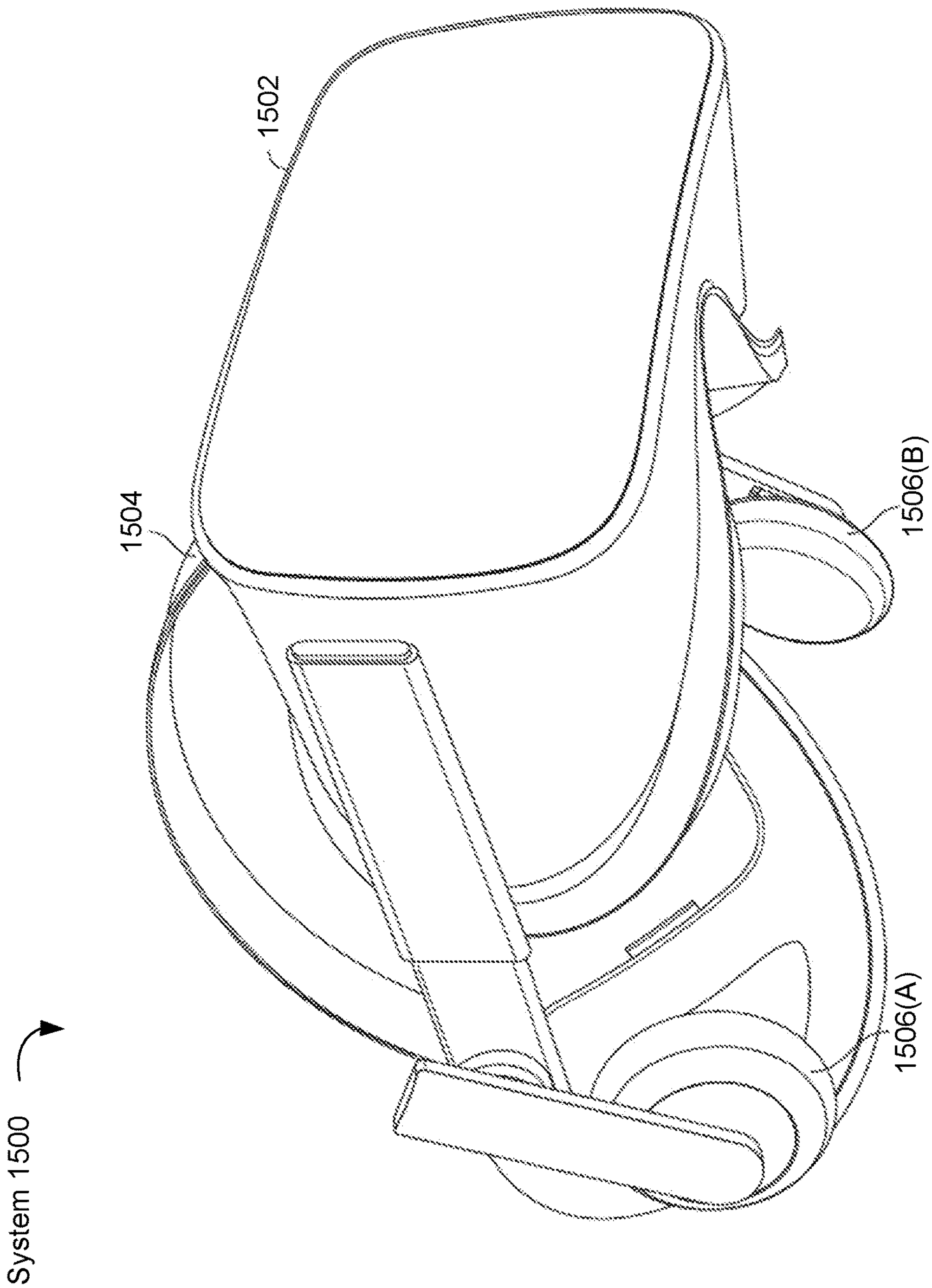


Figure 15

METHODS, DEVICES, AND SYSTEMS FOR CREATING HAPTIC STIMULATIONS AND TRACKING MOTION OF A USER

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application No. 62/636,699, filed Feb. 28, 2018, entitled "Methods, Devices, and Systems for Creating Haptic Stimulations and Tracking Motion of a User;" U.S. Provisional Application No. 62/647,559, filed Mar. 23, 2018, entitled "Methods, Devices, and Systems for Determining Contact On a User of a Virtual Reality and/or Augmented Reality Device;" U.S. Provisional Application No. 62/647,560, filed Mar. 23, 2018, entitled "Methods, Devices, and Systems for Projecting an Image Onto a User and Detecting Touch Gestures;" and U.S. Provisional Application No. 62/614,790, filed Jan. 8, 2018, entitled "Methods, Devices, and Systems for Creating Localized Haptic Sensations on a User," each of which is incorporated by reference herein in its entirety.

This application is related to U.S. Utility patent application Ser. No. 16/241,890 entitled "Methods, Devices, and Systems for Determining Contact On a User of a Virtual Reality and/or Augmented Reality Device," filed Jan. 7, 2019, U.S. Utility patent application Ser. No. 16/241,893, entitled "Methods, Devices, and Systems for Displaying a User Interface on a User and Detecting Touch Gestures," filed Jan. 7, 2019, and U.S. Utility patent application Ser. No. 16/241,900, entitled "Methods, Devices, and Systems for Creating Localized Haptic Sensations on a User," filed Jan. 7, 2019, each of which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

This relates generally to haptic stimulation and tracking motion, including but not limited to creating haptic stimulations on a user of a virtual and/or augmented reality devices and tracking motion of the user.

BACKGROUND

Virtual and augmented reality devices have wide applications in various fields, including engineering design, medical surgery practice, military simulated practice, video gaming, etc. Haptic or kinesthetic stimulations recreate the sense of touch by applying forces, vibrations, and/or motions to a user, and are frequently implemented with virtual and augmented reality devices. In certain applications, haptic stimulations are desired at locations where dexterity and motion of the user cannot be constrained. Conventional haptic creating devices (e.g., a glove or hand-held device), however, are not well suited for these applications.

Additionally, in order for virtual reality and augmented reality devices to function properly, a position of a user's extremities (e.g., arm, hand, etc.) generally needs to be known. In the past, cameras were used to determine the position of the user's extremities. Cameras, however, cannot adequately capture the intricacies of certain extremities, such as the human hand, especially when a full image of the human hand cannot be captured. As a result, challenges still exist with determining a position/pose of certain extremities (e.g., a pose of the user hand).

SUMMARY

Accordingly, there is a need for methods, devices, and systems that can (i) create haptic stimulations on a user without constraining dexterity and motion of the user and (ii) aid in determining a position of the user's extremities. One solution is a wearable device that does not encumber the user but is still able to create adequate haptic stimulations. The wearable device can also generate anatomical information (e.g., tomographic information) of a user of the wearable device, and facilitate creation of a partial representation of the user (e.g., a representation of the user's hand) from the anatomical information.

In some embodiments, the solution explained above can be implemented on a wearable device that includes a plurality of transducers (e.g., actuators). The wearable device in some instances is worn on the user's body (e.g., wrist, ankle, etc.) and can be used to stimulate areas of the body. Moreover, the wearable device can be in communication with a remote device (e.g., a virtual reality device and/or an augmented reality device, among others), and the wearable device can stimulate the body based on an instruction from the remote device.

As an example, the remote device may display media content (e.g., video data) or provide concomitant audio signals to a user (e.g., via a head-mounted display), and the remote device may also instruct the wearable device to create haptic stimulations that correspond to the media content. Additionally, the wearable device may collect anatomical information of the user and may relay the anatomical information to the remote device. In turn, the remote device may use the anatomical information to create a partial representation of the user (e.g., a representation of the user's hand) and may also incorporate the partial representation into the visual data. By using the anatomical information, the remote device is able to create a more accurate representation of the user's hand. The media content or the concomitant audio signals displayed by the host system could be used to modify the perceptual or cognitive interpretation of the stimulation (i.e. by displacing the perceived location of the stimulation towards a seen contact with an object, or by modifying the perceived pattern of vibration to be closer to the produced sound).

Thus, the devices, systems, and methods described herein provide benefits including but not limited to: (i) stimulating areas of the body that correspond to displayed visual data, (ii) creating anatomical information that improves the displayed visual data or other data gathered by sensors (e.g., sensors on the wearable device), (iii) the wearable device does not encumber free motion of a user's hand and/or wrist (or other body parts), and (iv) multiple wearable devices can be used simultaneously.

(A1) In accordance with some embodiments, a method is performed at a wearable device that includes a plurality of transducers that can each generate one or more waves (also referred to as "signals"). The method includes activating one or more first transducers of the plurality of transducers based on an instruction received from a remote device. Waves generated by the activated one or more first transducers provide a haptic stimulation. The method further includes activating one or more second transducers of the plurality of transducers. Waves generated by the activated one or more second transducers provide anatomical information of a user of the wearable device when the waves are received by one or more transducers of the plurality of transducers. In some embodiments, the anatomical information is tomographic information.

(A2) In some embodiments of the method of A1, the instruction received from the remote device corresponds to visual data displayed by a head-mounted display in communication with the remote device.

(A3) In some embodiments of the method of any of A1-A2, the wearable device also includes a radio, and the method further includes receiving, by the radio, the instruction from the remote device.

(A4) In some embodiments of the method of any of A1-A3, further including sending, by the radio, the anatomical information to the remote device after activating the one or more second transducers.

(A5) In some embodiments of the method of A4, the anatomical information, when received by the remote device, causes the remote device to: (i) generate at least a partial representation of the user of the wearable device from the anatomical information; and (ii) include the representation in the visual data displayed by the head-mounted display.

(A6) In some embodiments of the method of any of A1-A5, the anatomical information corresponds to a user's hand posture at a particular point in time.

(A7) In some embodiments of the method of any of A1-A6, the waves generated by the one or more first transducers are generated at a first frequency within a first frequency range, the waves generated by the one or more second transducers are generated at a second frequency within a second frequency range, and the second frequency range is different from the first frequency range.

(A8) In some embodiments of the method of any of A1-A7, the wearable device also includes a band configured to be secured around a wrist or ankle of the user, and each of the plurality of transducers is coupled to the band.

(A9) In some embodiments of the method of A8, transducers of the plurality of transducers are radially spaced along a perimeter of the band.

(A10) In some embodiments of the method of any of A8-A9, the one or more transducers of the plurality of transducers that receive the waves are opposite the one or more second transducers on the band.

(A11) In some embodiments of the method of any of A1-A10, transducers of the plurality of transducers are spaced equidistant from one another on the wearable device.

(A12) In some embodiments of the method of any of A1-A11, transducers in the plurality of transducers are arranged in columns on the wearable device, and transducers in a first respective column are adjacent to and parallel with corresponding transducers in a second respective column.

(A13) In some embodiments of the method of any of A1-A12, the waves generated by the plurality of transducers are ultrasonic waves.

(A14) In some embodiments of the method of any of A1-A13, activating the one or more first transducers and activating one or more second transducers comprises activating the one or more first transducers and the one or more second transducers simultaneously.

(A15) In some embodiments of the method of any of A1-A14, the one or more first transducers are activated at a first time and the one or more second transducers are activated a second time different from the first time.

(A16) In some embodiments of the method of any of A1-A15, the one or more transducers that receive the waves generated by the activated one or more second transducers include one or more transducers from (i) the one or more second transducers and/or (ii) the one or more first transducers.

(A17) In some embodiments of the method of any of A1-A16, the one or more first transducers include: (i) a first group of transducers that generates waves in a first direction, and (ii) a second group of transducers that generates waves in a second direction different from the first direction.

(A18) In some embodiments of the method of any of A1-A17, the one or more first transducers and the one or more second transducers are the same transducers.

In accordance with some embodiments, a wearable device includes one or more processors/cores and memory storing one or more programs configured to be executed by the one or more processors/cores. The one or more programs include instructions for performing the operations of the method described above (A1-A18). In accordance with some embodiments, a non-transitory computer-readable storage medium has stored therein instructions that, when executed by one or more processors/cores of a wearable device, cause the wearable device to perform the operations of the method described above (A1-A18). In accordance with some embodiments, a system includes a wearable device, a head-mounted display (HMD), and a computer system to provide video/audio feed to the HMD and instructions to the wearable device.

In another aspect, a wearable device is provided and the wearable device includes means for performing any of the methods described herein (A1-A18).

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the various described embodiments, reference should be made to the Description of Embodiments below, in conjunction with the following drawings in which like reference numerals refer to corresponding parts throughout the figures and specification.

FIG. **1** is a block diagram illustrating an exemplary haptics system, in accordance with various embodiments.

FIG. **2** is a block diagram illustrating an exemplary wearable device in accordance with some embodiments.

FIG. **3** is a block diagram illustrating an exemplary computer system in accordance with some embodiments.

FIG. **4** is an exemplary view of a wearable device on a user's wrist, in accordance with some embodiments.

FIG. **5**A is an exemplary cross-sectional view of a wearable device on the user's wrist in accordance with some embodiments.

FIG. **5**B is an exemplary cross-sectional view of a wearable device on the user's wrist in accordance with some embodiments.

FIG. **5**C is an example illustration of a hand shape model of a user, in accordance with some embodiments.

FIGS. **6**A and **6**B are exemplary views of a wearable device in accordance with some embodiments.

FIGS. **7**A and **7**B are cross-sectional views of the wearable device of FIG. **6**A in accordance with some embodiments.

FIG. **8** illustrates the wearable device of FIG. **6**A attached to a user's wrist in accordance with some embodiments.

FIGS. **9**A and **9**B are a different views of the wearable device of FIG. **6**A generating waves to create localized haptics stimulations in accordance with some embodiments.

FIGS. **9**C-**9**E are different views of the wearable device of FIG. **6**A generating waves to create haptics stimulations in accordance with some embodiments.

FIG. **10** is a flow diagram illustrating a method of generating haptic stimulations and topographic information in accordance with some embodiments.

FIG. **11** is a flow diagram illustrating a method of managing creation of haptic stimulations and anatomical information in accordance with some embodiments.

FIG. **12** illustrates multiple crawling waves constructively interfering with one another.

FIG. **13** illustrates an embodiment of an artificial reality device.

FIG. **14** illustrates an embodiment of an augmented reality headset and a corresponding neckband.

FIG. **15** illustrates an embodiment of a virtual reality headset.

DESCRIPTION OF EMBODIMENTS

Reference will now be made to embodiments, examples of which are illustrated in the accompanying drawings. In the following description, numerous specific details are set forth in order to provide an understanding of the various described embodiments. However, it will be apparent to one of ordinary skill in the art that the various described embodiments may be practiced without these specific details. In other instances, well-known methods, procedures, components, circuits, and networks have not been described in detail so as not to unnecessarily obscure aspects of the embodiments.

The terminology used in the description of the various described embodiments herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used in the description of the various described embodiments and the appended claims, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term "and/or" as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms "includes," "including," "comprises," and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

As used herein, the term "if" is, optionally, construed to mean "when" or "upon" or "in response to determining" or "in response to detecting" or "in accordance with a determination that," depending on the context. Similarly, the phrase "if it is determined" or "if [a stated condition or event] is detected" is, optionally, construed to mean "upon determining" or "in response to determining" or "upon detecting [the stated condition or event]" or "in response to detecting [the stated condition or event]" or "in accordance with a determination that [a stated condition or event] is detected," depending on the context.

As used herein, the term "exemplary" is used in the sense of "serving as an example, instance, or illustration" and not in the sense of "representing the best of its kind."

FIG. **1** is a block diagram illustrating a system **100**, in accordance with various embodiments. While some example features are illustrated, various other features have not been illustrated for the sake of brevity and so as not to obscure pertinent aspects of the example embodiments disclosed herein. To that end, as a non-limiting example, the system **100** includes a wearable device **102**, which is used in conjunction with a computer system **130** (e.g., a host system or a host computer). In some embodiments, the system **100** provides the functionality of a virtual reality device with haptics feedback, an augmented reality device with haptics feedback, a combination thereof, or provides some other functionality. The system **100** is described in greater detail below with reference FIGS. **13-15**.

An exemplary wearable device **102** (e.g., wearable device **102***a*) includes, for example, one or more processors/cores **104**, memory **106**, one or more transducer arrays **110**, one or more communications components **112** (also referred to herein as "radios"), and/or one or more sensors **114**. In some embodiments, these components are interconnected by way of a communications bus **108**. References to these components of the wearable device **102** cover embodiments in which one or more of these components (and combinations thereof) are included. In some embodiments, the one or more sensors **114** are part of the one or more transducer (e.g., transducers also perform the functions of the one or more sensors **114**, discussed in further detail below). For example, one or more transducers in the transducer array **110** may be electroacoustic transducers configured to detect acoustic waves (e.g., ultrasonic waves).

In some embodiments, each wearable device **102** includes one or more processors **104** that execute software modules for controlling operation of the wearable device **102**. In some embodiments, a single wearable device **102** (e.g., wearable device **102***a*) includes multiple processors **104**, such as one or more wearable device processors (configured to, e.g., control transmission of waves **116** by the transducer(s) **110**), one or more communications component processors (configured to, e.g., control communications transmitted by communications component **112** and/or receive communications by way of communications component **112**) and/or one or more sensor processors (configured to, e.g., control operation of sensor **114** and/or receive output from sensor **114**).

The wearable device **102** is configured to generate (and receive) waves **116** (signals), via the one or more transducers in a respective transducer array **110** (or a subset of the one or more transducers), that create one or more haptic stimulations felt by a user of the wearable device (i.e., at and near the immediate area of contact of the wearable device). In some embodiments, the wearable device **102** is also configured to generate waves **116** that provide anatomical information of a user of the wearable device **102** (e.g., when the waves are received by one or more transducers of the plurality of transducers). For example, if the wearable device is attached to the user's right wrist, then the anatomical information is of the right wrist. Further, the anatomical information can be used to determine a posture/pose of the user of the wearable device **102**. For example, the anatomical information for the user's right wrist can be used to determine a pose of the user's right hand. In some instances, the determined posture/pose can be further used to identity a gesture being made by the user. For example, the determined posture/pose may indicate that the user is making a pinch gesture with his right hand. In another example, the determined posture/pose may indicate that the user is pressing on a surface with one finger (or multiple fingers). In yet another example, the determined posture/pose may indicate that the user is making a full-hand swipe gesture or a finger swipe gesture. Various other gestures could also be detected and used to manipulate what is displayed by the head-mounted display.

In some embodiments, the one or more transducers are miniature piezoelectric actuators/devices, vibrotactile actuators, single or multipole voice coil motors, or the like. In some embodiments, the one or more transducers form one or more transducer arrays. In some embodiments, the waves **116** generated by the one or more transducers are mechanical waves (e.g., sound waves, ultrasonic waves, or various other mechanical waves). A mechanical wave is an oscillation of matter, which transfers energy through a medium. The "medium" may be air or the wearer's body. In some instances, oscillations or vibrations of the medium are similar to ripples created when an object impacts a body of water.

The computer system **130** is a computing device that executes virtual reality applications and/or augmented reality applications to process input data from the sensors **145** on the head-mounted display **140** and the sensors **114** on the wearable device **102**. The computer system **130** provides output data for (i) the electronic display **144** on the head-mounted display **140** and (ii) the wearable device **102** (e.g., processors **104** of the haptic device **102**, FIG. **2**A). An exemplary computer system **130**, for example, includes one or more processor(s)/core(s) **132**, memory **134**, one or more communications components **136**, and/or one or more cameras **139**. In some embodiments, these components are interconnected by way of a communications bus **138**. References to these components of the computer system **130** cover embodiments in which one or more of these components (and combinations thereof) are included.

The computer system **130** may be any suitable computer device, such as a laptop computer, a tablet device, a netbook, a personal digital assistant, a mobile phone, a smart phone, a virtual reality device (e.g., a virtual reality (VR) device, an augmented reality (AR) device, or the like), a gaming device, a computer server, or any other computing device. The computer system **130** is sometimes called a host, a host system, or a remote device.

The head-mounted display **140** presents media to a user. Examples of media presented by the head-mounted display **140** include images, video, audio, or some combination thereof. In some embodiments, audio is presented via an external device (e.g., speakers and/or headphones) that receives audio information from the head-mounted display **140**, the computer system **130**, or both, and presents audio data based on the audio information. The displayed images may be in virtual reality, augment reality, or mixed reality. An exemplary head-mounted display **140**, for example, includes one or more processor(s)/core(s) **141**, memory **142**, and/or one or more displays **144**. In some embodiments, these components are interconnected by way of a communications bus **146**. References to these components of the head-mounted display **140** cover embodiments in which one or more of these components (and combinations thereof) are included. It is noted that in some embodiments the head-mounted display **140** includes one or more sensors **145**. Alternatively, in some embodiments, the one or more sensors **145** are part of the computer system **130**. FIGS. **14** and **15** illustrate additional examples (e.g., AR system **1400** and VR system **1500**) of the head-mounted display **140**.

The electronic display **144** displays images to the user in accordance with data received from the computer system **130**. In various embodiments, the electronic display **144** may comprise a single electronic display or multiple electronic displays (e.g., one display for each eye of a user).

The sensors **145** include one or more hardware devices that detect spatial and motion information about the head-mounted display **140**. Spatial and motion information can include information about the position, orientation, velocity, rotation, and acceleration of the head-mounted display **140**. For example, the sensors **145** may include one or more inertial measurement units (IMUs) that detect rotation of the user's head while the user is wearing the head-mounted display **140**. This rotation information can then be used (e.g., by the computer system **130**) to adjust the images displayed on the electronic display **144**. In some embodiments, each IMU includes one or more gyroscopes, accelerometers, and/or magnetometers to collect the spatial and motion information. In some embodiments, the sensors **145** include one or more cameras positioned on the head-mounted display **140**.

In some embodiments, the computer system **130** is a standalone device that is coupled to the head-mounted display **140**. For example, the computer system **130** has one or more processors/cores **132** for controlling one or more functions of the computer system **130** and the head-mounted display **140** has one or more processors/cores **141** for controlling one or more functions of the head-mounted display **140**. Alternatively, in some embodiments, the head-mounted display **140** is a component of computer system **130**. For example, the one or more processors **132** control functions of the computer system **130** and the head-mounted display **140**. In addition, in some embodiments, the head-mounted display **140** includes the one or more processors **141** that communicate with the one or more processors **132** of the computer system **130**. In some embodiments, communications between the computer system **130** and the head-mounted display **140** occur via a wired connection between communications bus **138** and communications bus **146**. In some embodiments, the computer system **130** and the head-mounted display **140** share a single communications bus.

In some embodiments, the one or more cameras **139** of the computer system **130** are used to facilitate virtual reality and/or augmented reality. Moreover, in some embodiments, the one or more cameras **139** act as projectors to display the virtual and/or augmented images (or in some embodiments the computer system includes one or more distinct projectors). In some embodiments, the computer system **130** provides images captured by the one or more cameras **139** to the head-mounted display **140**, and the display **144** in turn displays the provided images. In some embodiments, the one or more processors **141** of the head-mounted display **140** process the provided images. In some embodiments, the one or more cameras **139** are part of the head-mounted display **140** (not shown).

Integrated circuits (not shown) of the wearable device **102**, such as a controller/control circuit and/or waveform generator, may control the behavior of the transducers (e.g., controller **412**, FIG. **4**). For example, based on the information (e.g., an instruction) received from the computer system **130** by way of a communication signal **118**, a controller may select values of waveform characteristics (e.g., amplitude, frequency, trajectory, direction, phase, pulse duration, among other characteristics) used for generating the waves **116** that would provide a sufficient haptic stimulation to be felt by the wearer/user. The controller further selects, at least in some embodiments, different values of the characteristics for the one or more transducers to create various haptic stimulations (e.g., pulsating feedback, impact feedback, rotational feedback, among others). In this way, the controller is able to create various haptic stimulations that mirror the visual data displayed by the head-mounted display **140**. The controller may also identify one or more transducers that would be effective in transmitting the waves **116** and may in turn activate the identified transducers. In some embodiments, the one or more processors **104** are a component of the controller and the one or more processors perform one or more of the operations described above.

The communications component **112** includes a communications component antenna for communicating with the computer system **130**. Moreover, the communications component **136** includes a complementary communications component antenna that communicates with the communications component **112**. The respective communication components are discussed in further detail below with reference to FIGS. **2** and **3**.

In some embodiments, data contained within communication signals **118** is used by the wearable device **102** for selecting specific values of characteristics used by the one or more transducers to transmit the waves **116**. In some embodiments, the data contained within the communication signals **118** alerts the computer system **130** that the wearable device **102** is ready for use. As will be described in more detail below, the computer system **130** sends instructions to the wearable device **102**, and in response to receiving the instruction, the wearable device generates waves **116** that create the haptic stimulation and/or the anatomical information. Although not shown, in some embodiments, the wearable device **102** is connected to the computer system **130** via a cable/wire and the communication between the wearable device **102** and the remote system **130** is through the cable/wire.

Non-limiting examples of sensors **114** and/or sensors **145** include, e.g., infrared, pyroelectric, ultrasonic, laser, optical, Doppler, gyro, accelerometer, resonant LC sensors, capacitive sensors, heart rate sensors, acoustic sensors, and/or inductive sensors. In some embodiments, sensors **114** and/or sensors **145** are configured to gather data that is used to determine a hand posture of a user of the wearable device and/or an impedance of the medium. Examples of sensor data output by these sensors include: body temperature data, infrared range-finder data, motion data, activity recognition data, silhouette detection and recognition data, gesture data, heart rate data, and other wearable device data (e.g., biometric readings and output, accelerometer data). In some embodiments, the one or more transducers serve as sensors.

As will be discussed in greater detail below, the haptic stimulation created by the wearable device **102** can correspond to visual data displayed by the head-mounted display **140**. To provide some context, the visual data displayed by the head-mounted display **140** may depict an insect crawling across the wearer's hand. The wearable device **102** may create one or more haptic stimulations to mimic, but not necessarily match, a feeling of the insect crawling across the wearer's hand. As one can imagine, an insect crawling across one's hand is a subtle feeling, and therefore the haptic stimulation created by the wearable device **102** would be equally subtle. Further, as the insect moves across the wearer's hand, so would a location (or locations) of the haptic stimulation. As another example, the visual data displayed by the head-mounted display **140** may depict the user shooting a bow and arrow. The wearable device **102** may create one or more haptic stimulations to mimic a feeling of the arrow releasing from the bow. As one can imagine, releasing an arrow from a bow creates a quick, yet intense feeling in the hands/forearms of the archer, and therefore the haptic stimulation created by the wearable device would be similarly intense. In yet another example, the visual data displayed by the head-mounted display **140** may depict a user in a dark cave, and therefore the user's visual sense in essence cannot be used. In such an example, the wearable device **102** may create one or more haptic stimulations to mimic sensations encountered in a cave, e.g., feeling of water dripping on the user, and/or bats flying past the user's arms, legs, and other body parts depending on the number of wearable devices **102** implemented.

In doing so, the user is further immersed in the virtual and/or augmented reality such that the user not only sees (at least in some instances) the visual data in the head-mounted display **140**, but also the user "feels" certain aspects of the displayed visual data. Moreover, the wearable device is designed to not restrict movement of the user's hand. For example, as shown in FIG. **8**, the wearable device **600** is attached to a wrist of the user and therefore the user's hand is unencumbered.

It is noted that the haptic stimulation created by the wearable device **102** can correspond to additional data or events (i.e., not limited to visual data displayed by the head-mounted display **140**). For example, the haptic stimulation created by the wearable device **102** can correspond to physiological information of the wearer. The physiological information may be gathered by sensors **114** of the wearable device **102** (e.g., IMU, heart rate sensor, etc.) and/or sensors of other devices (e.g., sensors **145** and cameras **139**). The haptic stimulation may also correspond to proprioceptive events, such as mechanical stimulations produced by the user (e.g., when the wearer taps on a virtual object). Information for mechanical stimulations can also be gathered by sensors **114** of the wearable device **102** and/or sensors of other devices (e.g., sensors **145** and cameras **139**).

Additionally, as will be discussed in greater detail below, the anatomical information gathered by the wearable device **102** can be used by the computer system **130** and/or the head-mounted display **140** to generate the visual data to be displayed by the head-mounted display **140**. For example, the anatomical information may be tomographic information, and the tomographic information generated by the wearable device **102** may indicate that the user's hand is in a fist. As a result, the computer system **130** and/or the head-mounted display **140** may update the visual data to reflect the fact that the user's hand is in a fist. This is particularly useful when the user's hand is obstructed such that camera(s) **139** cannot capture the user's hand. In some embodiments, information captured from the camera(s) **139** and the anatomical information generated by the wearable device **102** are used in conjunction to generate the visual data.

FIG. **2** is a block diagram illustrating a representative wearable device **102** in accordance with some embodiments. In some embodiments, the wearable device **102** includes one or more processors/cores (e.g., CPUs, microprocessors, and the like) **104**, one or more communication components **112**, memory **106**, one or more transducer arrays **110**, and one or more communication buses **108** for interconnecting these components (sometimes called a chipset). In some embodiments, the wearable device **102** includes one or more sensors **114** as described above with reference to FIG. **1**. In some embodiments (not shown), the wearable device **102** includes one or more output devices such as one or more indicator lights, a sound card, a speaker, a small display for displaying textual information and error codes, etc. In some embodiments (not shown), the one or more processors/cores are part of a controller (e.g., controller **412**, FIG. **4**).

In some embodiments, transducers in a respective transducer array **110** include, e.g., hardware capable of generating the waves **116** (e.g., soundwaves, ultrasound waves, electromagnetic waves, etc.). For example, each transducer can convert electrical signals into ultrasound waves (or various other waves). The transducers may be miniature piezoelectric transducers, capacitive transducers, single or multipole voice coil motors, and/or any other suitable device for creation of waves **116**.

In some embodiments, the one or more transducer arrays **110** are coupled with (or include) an oscillator and/or a frequency modulator that is used to generate the waves so that the waves are appropriate for transmission. The oscillator and the frequency modulator may be part of an integrated circuit included in the wearable device **102**.

The communication component(s) **112** (sometimes referred to herein "radio(s)") enable communication between the wearable device **102** and other devices (e.g., the computer system **130**). In some embodiments, the communication component(s) **112** include, e.g., hardware capable of data communications using any of a variety of wireless protocols (e.g., IEEE 802.15.4, Wi-Fi, ZigBee, 6LoWPAN, Thread, Z-Wave, Bluetooth Smart, ISA100.11a, WirelessHART, MiWi, etc.) wired protocols (e.g., Ethernet, HomePlug, etc.), and/or any other suitable communication protocol, including communication protocols not yet developed as of the filing date of this document.

The memory **106** includes high-speed random access memory, such as DRAM, SRAM, DDR SRAM, or other random access solid state memory devices; and, optionally, includes non-volatile memory, such as one or more magnetic disk storage devices, one or more optical disk storage devices, one or more flash memory devices, or one or more other non-volatile solid state storage devices. The memory **106**, or alternatively the non-volatile memory within memory **106**, includes a non-transitory computer-readable storage medium. In some embodiments, the memory **106**, or the non-transitory computer-readable storage medium of the memory **106**, stores the following programs, modules, and data structures, or a subset or superset thereof:

- operating logic **216** including procedures for handling various basic system services and for performing hardware dependent tasks;
- communication module **218** for coupling to and/or communicating with remote devices (e.g., computer system **130**, other wearable devices, etc.) in conjunction with communication component(s) **112**;
- sensor module **220** for obtaining and processing sensor data (e.g., in conjunction with sensor(s) **114** and/or transducer arrays **110**) to, for example, determine an orientation of the wearable device **102** (among other purposes such as determining hand pose of the user of the wearable device);
- wave generating module **222** for generating and transmitting (e.g., in conjunction with transducers(s) **110**) waves, including but not limited to creating haptic stimulation(s) and anatomical information). In some embodiments, the wave generating module **222** also includes or is associated with a characteristic selection module that is used to select values of characteristics for generating the waves; and
- database **224**, including but not limited to:
  - sensor information **226** for storing and managing data received, detected, and/or transmitted by one or more sensors (e.g., sensors **114**, one or more remote sensors, and/or transducer arrays **110**), including anatomical information;
  - device settings **228** for storing operational settings for the wearable device **102** and/or one or more remote devices (e.g., selected values of characteristics for the waves);
  - communication protocol information **230** for storing and managing protocol information for one or more protocols (e.g., custom or standard wireless protocols, such as ZigBee, Z-Wave, etc., and/or custom or standard wired protocols, such as Ethernet); and
  - known impedances information **232** for storing impedances for various users of the wearable device.

In some embodiments, the characteristic selection module of the wave generating module **222** is used to select a particular frequency at which to transmit the waves. As discussed above, other characteristics for waves may include phase, gain, amplitude, direction, and the selection module may select particular values for each of those characteristics. In some embodiments, the characteristic selection module selects the values based on information received from the computer system **130** (as explained greater detail below). In some embodiments, the computer system **130** includes the characteristic selection module and provides the relevant characteristics to the wearable device **102**.

In some embodiments (not shown), the wearable device **102** includes a location detection device, such as a GNSS (e.g., GPS, GLONASS, etc.) or other geo-location receiver, for determining the location of the wearable device **102**. Further, in some embodiments, the wearable device **102** includes location detection module (e.g., a GPS, Wi-Fi, magnetic, or hybrid positioning module) for determining the location of the wearable device **102** (e.g., using the location detection device) and providing this location information to the computer system **130**.

In some embodiments (not shown), the wearable device **102** includes a unique identifier stored in database **224**. In some embodiments, the wearable device **102** sends the unique identifier to the computer system **130** to identify itself to the computer system **130**. This is particularly useful when multiple wearable devices are being concurrently used.

In some embodiments (not shown), the wearable device **102** includes an inertial measurement unit (IMU) for detecting motion and/or a change in orientation of the wearable device **102**. In some embodiments, the detected motion and/or orientation of the wearable device **102** (e.g., the motion/change in orientation corresponding to movement of the user's hand) is used to manipulate an interface (or content within the interface) displayed by the head-mounted display **140**. In some embodiments, the IMU includes one or more gyroscopes, accelerometers, and/or magnetometers to collect IMU data. In some embodiments, the IMU measures motion and/or a change in orientation for multiple axes (e.g., three axes, six axes, etc.). In such instances, the IMU may include one or more instruments for each of the multiple axes.

Each of the above-identified elements (e.g., modules stored in memory **106** of the wearable device **102**) is optionally stored in one or more of the previously mentioned memory devices, and corresponds to a set of instructions for performing the function(s) described above. The above identified modules or programs (e.g., sets of instructions) need not be implemented as separate software programs, procedures, or modules, and thus various subsets of these modules are optionally combined or otherwise rearranged in various embodiments. In some embodiments, the memory **106**, optionally, stores a subset of the modules and data structures identified above. Furthermore, the memory **106**, optionally, stores additional modules and data structures not described above.

FIG. **3** is a block diagram illustrating a representative computer system **130** in accordance with some embodiments. In some embodiments, the computer system **130** includes one or more processors/cores (e.g., CPUs, GPUs, microprocessors, and the like) **132**, one or more communication components **136**, memory **134**, one or more cameras **139**, and one or more communication buses **138** for interconnecting these components (sometimes called a chipset). In some embodiments, the computer system **130** includes a head-mounted display interface **305** for connecting the computer system **130** with the head-mounted display **140**. As discussed above in FIG. **1**, in some embodiments, the computer system **130** and the head-mounted display **140** are together in a single device, whereas in other embodiments the computer system **130** and the head-mounted display **140** are separate from one another (e.g., two separate device connected wirelessly or wired).

Although not shown, in some embodiments, the computer system **130** (and/or the head-mounted display **140**) includes one or more sensors **145** (as discussed above with reference to FIG. **1**).

The communication component(s) **136** enable communication between the computer system **130** and other devices (e.g., wearable devices **102***a* . . . **102***n*). In some embodiments, the communication component(s) **136** include, e.g., hardware capable of data communications using any of a variety of custom or standard wireless protocols (e.g., IEEE 802.15.4, Wi-Fi, ZigBee, 6LoWPAN, Thread, Z-Wave, Bluetooth Smart, ISA100.11a, WirelessHART, MiWi, etc.), custom or standard wired protocols (e.g., Ethernet, HomePlug, etc.), and/or any other suitable communication protocol, including communication protocols not yet developed as of the filing date of this document.

The memory **134** includes high-speed random access memory, such as DRAM, SRAM, DDR SRAM, or other random access solid state memory devices; and, optionally, includes non-volatile memory, such as one or more magnetic disk storage devices, one or more optical disk storage devices, one or more flash memory devices, or one or more other non-volatile solid state storage devices. The memory **134**, or alternatively the non-volatile memory within memory **134**, includes a non-transitory computer-readable storage medium. In some embodiments, the memory **134**, or the non-transitory computer-readable storage medium of the memory **134**, stores the following programs, modules, and data structures, or a subset or superset thereof:

- operating logic **316** including procedures for handling various basic system services and for performing hardware dependent tasks;
- communication module **318** for coupling to and/or communicating with other devices (e.g., wearable devices **102***a*-**102**-*n*, a remote server (not shown), etc.) in conjunction with communication component(s) **136**;
- virtual-reality generation module **320** that is used for generating virtual-reality images and sending corresponding video and audio data to the HMD **140** (in some embodiments, the virtual-reality generation module **320** is an augmented-reality generation module **320** (or the memory **134** includes a distinct augmented-reality generation module) that is used for generating augmented-reality images and projecting those images in conjunction with the camera(s) **139** and the HMD **140**);
- instruction generation module **322** that is used for generating an instruction that, when sent to the wearable device **102** (e.g., using the communications component **136**), causes the wearable device **102** to activate one or more transducers;
- display module **324** that is used for displaying virtual-reality images and/or augmented-reality images in conjunction with the head-mounted display **140** and/or the camera(s) **139**;
- database **326**, including but not limited to:
  - display information **328** for storing virtual-reality images and/or augmented-reality images (e.g., visual data);
  - haptics information **330** for storing haptics information that corresponds to the stored virtual-reality images and/or augmented-reality images;
  - communication protocol information **332** for storing and managing protocol information for one or more protocols (e.g., custom or standard wireless protocols, such as ZigBee, Z-Wave, etc., and/or custom or standard wired protocols, such as Ethernet); and
  - mapping data **334** for storing and managing mapping data (e.g., mapping one or more wearable devices **102** on a user).

In the example shown in FIG. **3**, the computer system **130** further includes virtual-reality (and/or augmented-reality) applications **336**. In some embodiments, the virtual-reality applications **336** are implemented as software modules that are stored on the storage device and executed by the processor. Each virtual-reality application **336** is a group of instructions that, when executed by a processor, generates virtual reality content for presentation to the user. A virtual-reality application **336** may generate virtual-reality content in response to inputs received from the user via movement of the head-mounted display **140** or the wearable device **102**. Examples of virtual-reality applications **336** include gaming applications, conferencing applications, and video playback applications.

The virtual-reality generation module **320** is a software module that allows virtual-reality applications **336** to operate in conjunction with the head-mounted display **140** and the wearable device **102**. The virtual-reality generation module **320** may receive information from the sensors **145** on the head-mounted display **140** and may, in turn provide the information to a virtual-reality application **336**. Based on the received information, the virtual-reality generation module **320** determines media content to provide to the head-mounted display **140** for presentation to the user via the electronic display **144**. For example, if the virtual-reality generation module **320** receives information from the sensors **145** on the head-mounted display **140** indicating that the user has looked to the left, the virtual-reality generation module **320** generates content for the head-mounted display **140** that mirrors the user's movement in a virtual environment.

Similarly, in some embodiments, the virtual-reality generation module **320** receives information from the sensors **114** on the wearable device **102** and provides the information to a virtual-reality application **336**. The application **336** can use the information to perform an action within the virtual world of the application **336**. For example, if the virtual-reality generation module **320** receives information from the sensors **114** that the user has raised his hand, a simulated hand (e.g., the user's avatar) in the virtual-reality application **336** lifts to a corresponding height. As noted above, the information received by the virtual-reality generation module **320** can also include information from the head-mounted display **140**. For example, cameras **139** on the head-mounted display **140** may capture movements of the user (e.g., movement of the user's arm), and the application **336** can use this additional information to perform the action within the virtual world of the application **336**.

To further illustrate with an augmented reality example, if the augment-reality generation module **320** receives information from the sensors **114** that the user has rotated his forearm while, in augmented reality, a user interface (e.g., a keypad) is displayed on the user's forearm, the augmented-reality generation module **320** generates content for the head-mounted display **140** that mirrors the user's movement in the augmented environment (e.g., the user interface rotates in accordance with the rotation of the user's forearm).

In some embodiments, the virtual-reality generation module **320** includes a representation generation module. The representation generation module is used for generating at least a partial representation of the user (e.g., a pose of the user's hand) of the wearable device **102** from anatomical information received from the wearable device **102**. Further, in some embodiments, the virtual-reality generation module **320** then includes the representation in the visual data to be displayed by the head-mounted display **140**. In some embodiments, the virtual-reality generation module **320** includes a gesture recognizing module that is used for identifying a hand gesture based on the partial representation of the user generated by the representation generation module.

In some embodiments, the display information **328** includes anatomical information provided by one or more wearable devices **102**. Further, in some embodiments, the display information **328** includes representations (or partial representations) of the user of the wearable device generated from the anatomical information by the representation generation module.

In some embodiments, the known impedances information **232** are also (or only) stored at the computer system **130**.

Each of the above identified elements (e.g., modules stored in memory **134** of the computer system **130**) is optionally stored in one or more of the previously mentioned memory devices, and corresponds to a set of instructions for performing the function(s) described above. The above identified modules or programs (e.g., sets of instructions) need not be implemented as separate software programs, procedures, or modules, and thus various subsets of these modules are optionally combined or otherwise rearranged in various embodiments. In some embodiments, the memory **134**, optionally, stores a subset of the modules and data structures identified above.

FIG. **4** is an example view of the wearable device **400** in accordance with some embodiments. The wearable device **400** is an example of the wearable device **102**. The view shows the user's hand **408**, user's wrist **404**, user's arm **406**, and the wearable device **400** on the user's arm **406**. Such an arrangement is merely one possible arrangement, and one skilled in the art will appreciate that the discussion below is not limited to the arrangement shown in FIG. **4**.

The wearable device **400** includes a wearable structure **402** that may be a flexible mechanical substrate such as a plastic (e.g., polyethylene or polypropylene), rubber, nylon, synthetic, polymer, etc. In some embodiments, the wearable structure **402** is configured to be worn around at least a portion of a user's wrist or arm **404**/**406** (and various other body parts). In some embodiments, the wearable structure **402** is a continuous band (e.g., does not break apart). In some embodiments, the wearable structure **402** includes two ends that can be connected and broken apart (e.g., similar to the ends of a watch). In some embodiments, the wearable structure **402** is referred to herein as a band.

The wearable device **400** includes a transducer array **110** having a plurality of transducers **410** arranged at different locations on the wearable structure **402**. The transducers **410** can be arranged in a pattern along an inner surface of the wearable structure **402** facing the arm **406** such that the transducers **410** contact the user's skin. In another example, the transducers can be arranged in a radial pattern along an inner perimeter of the wearable structure **602** (FIG. **6**B).

Each transducer **410** can generate one or more waves (e.g., waves **116**, FIG. **1**) in response to receiving one or more control signals from a controller **412**. The one or more control signals, at least in some embodiments, instruct one or more of the transducers **410** to generate one or more waves (e.g., ultrasonic waves). In some embodiments, the one or more transducers **410** transmit waves into the user's wrist (e.g., to gather anatomical information as shown and described with reference to FIGS. **5**A-**5**B and/or to create haptic stimulations as shown and described with reference to FIGS. **9**A-**9**E). Alternatively or in addition, the one or more transducers **410** transmit one or more waves perpendicular the user's wrist (e.g., to create haptic stimulations).

In some embodiments, the one or more transducers **410** can operate in different modes either simultaneously or in temporal/frequency modulated modes, generating different types of waves **116** that interact with the tissue in different ways. The extra wave types can be utilized to retrieve more abundant information regarding both the static and dynamic, both the anatomical and functional information of the human body, which is further utilized to improve performance. Alternatively or in addition, the operating modes of the one or more transducers **410** can be specifically designed to optimize the stimulation and tracking performance, either via grid-search in parameter space or simulation studies. For example, using visible light near forearm and using near-infrared near wrist may yield better results for certain interaction tasks.

In those embodiments where the one or more transducers **410** transmit waves into the user's wrist to gather anatomical information, the gathered anatomical information can be used to determine a hand pose (among other things) of the user. For example, the captured waves correspond to movement and/or a state of internal bodily structures within the user's wrist or arm **406**. A hand position (or hand pose) includes the angle and position of the palm, knuckles, and fingers of the user's hand and includes parameters corresponding to joints of the hand, edges between pairs of the joints, and angles between pairs of the edges, as illustrated and described in greater detail below with reference to FIG. **5**C. In some embodiments, the wearable device **400** includes one or more sensors (e.g., sensors **114**, FIG. **1**) mounted on the wearable structure **402** to measure impedance of the user's wrist or arm. In some embodiments, anatomical information gathered by the wearable device **400** may be used to render a full hand model in a virtual reality system and/or track human-object interaction in real environments.

In those embodiments where the one or more transducers **410** transmit waves into the user's wrist to gather raw sensor information, and such procedure is repeated on multiple users for multiple trials to form a database. Computer models, both algebraic algorithms based on anatomical information or heuristic observations, and machine learning algorithms that generate a mapping based on the collected database, can be established to determine a hand pose of the user.

In those embodiments where the one or more transducers **410** transmit waves to create haptic stimulations, each transducer **410** on the wearable device **400** functions individually to create the haptic stimulation. Alternatively, in some embodiments, two or more transducers function together to create the haptic stimulation. In some embodiments, less than all the transducers function to create the haptic stimulation. For example, a first group of transducers (one or more transducers) may function to create first haptic stimulation and a second group of transducers having at least one different transducer may function to create second haptic stimulation. In some embodiments, a threshold number of transducers is needed to create the haptic stimulation. For example, two or more transducers need to generate waves in order for the haptic stimulation to be felt by a user of the wearable device. In some embodiments, a magnitude of the haptic stimulation felt by the user increases as the number of transducers generating waves increases. “Haptic stimulations” (e.g., tactile feedback) include but are not limited to a touch stimulation, a swipe stimulation, a pull stimulation, a push stimulation, a rotation stimulation, a heat stimulation, and/or a pain stimulation. Haptic stimulations are discussed in further detail below with reference to FIGS. **9**A-**9**E.

In some embodiments, the transducers **410** are designed to make contact with human skin. A contact area having a conductive agent and padding may be used on the wearable device **400** behind each transducer to improve subject comfort and reduce contact impedances (e.g., conductive agent **502**, FIG. **5**A). The conductive agent between the transducer and skin may be a “wet” connection using a conductive gel, which may consist of propylene glycol and NaCl, or a “dry” connection, such as a thin layer of conductive polymer (e.g., carbon-doped PDMS).

It is further noted that the description below with reference to FIGS. **5**A-**5**C applies equally to the wearable device **600**. In other words, the wearable device **600** can also be used to generate anatomical information (e.g., tomographic information).

FIG. **5**A is an example cross sectional view **500** of the wearable device **400** taken along the X-Y line shown in FIG. **4**, in accordance with some embodiments. The cross sectional view **500** shows the user’s arm **406** and a tendon **505** within the user’s arm **406**. In this particular example, the transducers **410** do not fully wrap around the wrist (e.g., transducers **410**-A-**410**-D are disposed on one side of the user’s arm **406**).

One or more of the transducers **410**-A-**410**-D can generate waves (e.g., waves **504**-A and **504**-B) in the user’s arm **406**. The generated waves **504**-A and **504**-B extend into the user’s body (e.g., extend into the epidermis, the dermis, the muscles, the tendons, the ligaments, the bones, etc.) and may be used to gather anatomical information about the user, which is in turn used to determine a hand pose of the user. In some embodiments, each transducer **410** varies one or more of a time period of the wave, an amplitude of the wave, and a phase of the wave when generating the waves.

In some embodiments, the wearable device **400** uses ultrasound computer tomography (USCT) to generate tomographic information. USCT involves generating one or more waves (e.g., ultrasound waves) from one or more transducers **410** (e.g., piezoelectric ultrasound transducers) in the direction of the object to be measured (e.g., toward the user’s wrist/forearm/hand, as shown in FIG. **5**A). The transmitted waves are then received by other transducers (e.g., as shown in FIG. **5**B) or by the same transducers that generated the one or more waves (e.g., as shown in FIG. **5**A), or some combination thereof. While travelling to the receiving location, the one or more waves interact with one or more objects (e.g., muscles, tendons, bones, blood vessels, skin, etc.) and as a consequence, the one or more waves may be altered by the object(s). The altered ultrasound waves reveal information about the object(s), and after being received, the information from the altered one or more waves can be processed and used to create an image of the object(s) (e.g., create an image of the user’s muscles, tendons, bones, blood vessels, skin, etc. below the wearable device). In some instances, multiple forms of information can be extracted from the altered waves. For example, the information can include but is not limited to: attenuation the wave’s sound pressure experiences indicate on the object’s attenuation coefficient, the time-of-flight of the wave provides speed of sound information, and scattering of the wave indicates the echogenicity of the object (e.g. refraction index, surface morphology, etc.). For example, as shown in FIG. **5**B, the generated wave **512**-A changes direction upon interacting with the tendon **505**, and the refracted wave **514**-A results.

In FIG. **5**A, the generated waves **504**-A, **504**-B, or a portion of the waves **504**-A, **504**-B, are reflected by the tendon **505** and/or a portion of the wearable structure **402**. As a result, the reflected waves **506**-A, **506**-B are received by the transducers **410**-A and **410**-D. In some instances, the same transducers that generate the waves do not receive the waves. For example, in FIG. **5**B, the generated waves **512**-A, **512**-B, which are generated by transducers **410**-A and **410**-C, are alter by the tendon **505** and the refracted waves **514**-A, **514**-B are then received by transducers **410**-F and **410**-H. It is noted that other techniques known by those skilled in the art can be used to generate the tomographic information (e.g., electrical impedance tomography, infrared tomography, pressure tomography, and the like). Additionally, in some embodiments, the anatomical information is not tomographic information. Instead, the anatomical information is derived from direct voltage changes and other non-image sensor analysis.

The wearable device **400** may measure any or all of muscle contractions, tendon **505** motion, tendon **505** length, and joint stiffness in order to determine, as an example, the hand position of the user’s hand **408** (e.g., using USCT, or other similar techniques). For example, combinations of such values measured from the user’s arm **406** can indicate the angle formed by bones between joints within the user’s hand **408**. The position of the hand can be represented by a collection of values representing the angles formed between joints in the hand as derived from the waves.

The wearable device **400** operates by determining the state of structures within the user’s body, e.g., state of structures within the arm **406** that is connected to the hand **408** by the wrist. For example, the state of bones such as the radius and ulna, the radial styloid and the ulnar styloid, the carpal bones, the metacarpals, etc., may be determined to identify the position of the user’s hand **408**. The state of joints such as the carpometacarpophalangeal joint, the metacarpophalangeal joint, and the interphalangeal joint, etc., may be determined from the waves to identify the position of the user’s hand **408**. The state of muscles such as intrinsic muscles, tendons such as the flexor tendons, extensor tendons, tendon sheaths, and median nerve and ulnar nerve may be determined from the waves to identify the position of the user’s hand **408**. Among other advantages, the wearable device **400** can determine user hand pressure when holding objects and can distinguish between a user who is grasping an object in the hand **408** and a user who is making a grasping gesture with an empty hand **408**.

In some embodiments, the transducers **410** transmit waves into the user’s body in a staggered manner, where a different subset of the transducers transmit waves at different times. In some embodiments, the remaining transducers may be used to measure the altered waves. This procedure may then be repeated for multiple stimulation patterns defining an order of pairs of transducers selected to emit the waves.

The anatomical information (e.g., tomographic information) derived from the waves/signals may be sent to a computing system **130** (e.g., a separate host system or a processor integrated with the wearable device **400**) to perform image reconstruction and display based at least in part on the waves. In other example, the computing system **130** may use the anatomical information of the user's wrist to determine a position/pose of the user's hand attached to said wrist.

FIG. **5**B is an example cross sectional view **510** of the wearable device **400** taken along the X-Y line shown in FIG. **4**, in accordance with some embodiments. The cross sectional view **510** shows the user's arm **406** and a tendon **505** within the user's arm **406**. In this particular example, the transducers **410** wrap fully around the wrist (e.g., transducers **410**-A-**410**-H are disposed around the user's arm **406**). One or more transducers on one side of the arm **406** may generate waves (e.g., waves **512**-A and **512**-B) into the user's arm and one or more transducers on another side of the arm **406** may receive waves (e.g., waves **514**-A and **514**-B) traveling through the tendon **505** of the user's arm **406**. In this manner, the system is able to measure cross-sectional impedance properties of the wrist or arm **406**. It is noted in some embodiments, a combination of what is shown in FIG. **5**A and what is shown in FIG. **5**B is obtained (e.g., some waves reflect back towards the direction of generation as shown in FIG. **5**A while some waves continue toward the other side of the wearable device **400**).

FIG. **5**C is an example illustration of a hand shape model **520** of a user in accordance with some embodiments. In some embodiments, the hand position of the user is represented with reference to the hand shape model **520**. For example, the tomographic information gathered using USCT may be compared to the hand shape model **520**. In some embodiments, the hand shape model **520** is stored in the memory **106** and/or the memory **134**.

The hand shape model **520** includes parameters that correspond to joints of the hand **406** of the wrist or arm **408** of the user, edges between pairs of the joints, range of angles between pairs of the edges, and a mesh including vertices and for each vertex, a relationship (e.g., distance) between the vertex and one or more joints. In some embodiments, the waves (e.g., sound waves, ultrasound waves, etc.) generated by the wearable device **400** are used to determine the hand position with reference to the hand shape model **520**, such as the angles defined between pairs of edges between joints.

The hand shape model **520** defines a deformable shape and size of the hand **120**. For example, hand shape model **520** includes a skeleton **522** and a mesh **524**. The skeleton **522** includes hand features **526**, representing nodes (joints) of the skeleton **522**. At least some hand features **526** have fixed distances between other hand features **526**, which is shown by the hand edges **528** of the skeleton **522**. The hand edges **528** are models for bones of the hand **408**, and the hand features **526** are models for joints that connect the bones.

Each hand feature **526** is associated with one or more degrees of freedom (DOF) defining the range of motion of the joint. For example, the hand feature at the wrist includes two degrees of freedom (e.g., pitch and yaw). In another example, the hand features **526** at each knuckle include two degrees of freedom (e.g., roll and yaw). In yet another example, the hand features **526** at each finger joint include one degree of freedom (e.g., yaw). Degrees of freedom may include rotational or translational degrees of freedom. Each degree of freedom may be associated with a range of values, such as may be defined by a maximum value and a minimum value, representing how much a joint can move along the degree of freedom. A hand position is defined by a particular state of the hand shape model **520**. For example, a set of values for each degree of freedom of the hand features **526** may define a particular hand pose.

The mesh **524** of the hand shape model **520** defines the surface of the user hand model **520**. The mesh **524** may include vertices, where each vertex is attached with a part of the skeleton **522**, such as a hand feature **526** or location along a hand edge **528**. The vertices when interconnected form a polygon mesh defining a model of the hand surface. For example, a vertex may have a predefined distance from an attached hand feature **526**. If a hand feature **526** is moved, the attached vertices move accordingly such that the mesh **524** changes with movement of the skeleton **522**. In some embodiments, vertices of the mesh **524** may be attached to more than one location of the skeleton **522**.

FIG. **6**A is an isometric view of the wearable device **600** in accordance with some embodiments. The wearable device **600** is an example of the wearable device **102**. The wearable device **600** is configured to be attached to a part of a user's body. For example, the wearable device **600** is configured to be attached to a wrist, forearm, ankle, bicep, calf, thigh, and various other parts of the user's body. In some embodiments, the wearable device **600** is a rigid or semi-rigid structure. Alternatively, in some embodiments, the wearable device **600** is a flexible structure. Although the wearable device **600** is shown as a continuous circle, the wearable device **600** may break apart to be attached to the user's body (e.g., in a similar fashion to a watch).

FIG. **6**B is a cross-sectional view of the wearable device **600** in accordance with some embodiments. The wearable device **600** further includes a plurality of transducers **410** (FIG. **4**) positioned along an inner perimeter of the wearable structure **602**. The transducers **410** in this example are radially spaced, such that the transducers **410** wrap around the wearable structure **602** and form a substantially contiguous circle of transducers. In such an arrangement, the wearable device **600** is able to produce waves **116** in a 360-degree fashion. In some embodiments, the wearable structure **602** separates the transducers **410** from the user's skin. Alternatively, in some embodiments (not shown), the transducers **410** are in direct contact with the user's skin (a conductive agent may also be included, as described above with reference to FIG. **4**).

FIGS. **7**A-**7**B are cross-sectional views of the wearable device **600** in accordance with some embodiments. FIG. **7**A illustrates a single arrangement of transducers **410** along a length of the wearable structure **602**. FIG. **7**B illustrates a double arrangement of transducers **410**A, **410**B along the length of the wearable structure **602** (other arrangements are possible, such as a triple arrangement). In some embodiments (not shown), the transducers are staggered such that transducers in a given row are not parallel, but are instead offset from one another.

FIG. **8** illustrates the wearable device **600** attached to a user's wrist. Left of the wearable device **600** is the user's arm **802** and right of the wearable device **600** is the user's hand **804**. The wearable device **600** could also be attached to a user's ankle, or various other body parts.

The discussion below with reference to FIGS. **9**A-**9**B describes a process for creating localized haptic stimulations on a user of the wearable device (e.g., waves **116** stimulate areas of the wearer's body outside of the wearable device's **600** immediate area of contact).

FIG. **9**A is a cross-sectional view **900** of the wearable device **600** taken along "A" view, in accordance with some embodiments. The user's arm has been removed from FIG. **9**A for ease of illustration. In this particular example, two transducers **410**A, **410**B are activated (indicated by shading), and each is generating a respective wave **116***a*, **116***b*. In some embodiments, the wearable device **600** selectively activates a subset of the transducer array **110** (e.g., two shaded transducers **410**A and **410**B) based at least in part on a desired target location. In response to being activated, the two transducers **410**A and **410**B each generates a wave **116***a*, **116***b* that impacts the user's body at an impact location. The generated waves **116***a*, **116***b*, at least initially, travel perpendicular to the user's skin.

FIG. **9**B is an example top view **902** that shows the wearable device **600** and the user's arm taken along "B" view, in accordance with some embodiments. The two waves **116***a*, **116***b* generated by the two transducers **410**A and **410**B now parallel the user's body and are using the hand **804** as a medium. The two waves **116***a*, **116***b* propagate within a sublayer of the body away from an impact location. In some embodiments, a direction of the two waves **116***a*, **116***b* is different, such as normal to and tangential with the skin, which can lead to different conduction velocities and attenuation. For example, one of the waves may initially travel perpendicular to the user's arm while another wave may initially travel parallel to the user's arm.

Values for characteristics of each wave are selected by the wearable device **600** (or the host system **130**) so that the two waves **116***a*, **116***b* constructively interfere at the target location **912**. The two waves **116***a*, **116***b* in FIG. **9**B are shown as being substantially sinusoidal in shape. However, in some instances, the two waves **116***a*, **116***b* resemble ripples on a body of water (e.g., as shown in FIG. **12**). In such instances, the first wave **116***a* creates a first ripple (e.g., a first crawling wave) that propagates within a sublayer of the body away from the impact location and the second wave **116***b* creates a second ripple (e.g., a second crawling wave) that propagates within a sublayer of the body away from the impact location. Based on the characteristics of the ripples, the propagation medium, and a spacing of the two impact locations, the two waves **116***a*, **116***b* constructively interfere at the target location **912**.

Constructive interference of waves occurs when two or more waves **116** are in phase with each other and converge into a combined wave such that an amplitude of the combined wave is greater than amplitude of a single one of the waves. For example, the positive and negative peaks of sinusoidal waveforms arriving at a location from multiple transducers "add together" to create larger positive and negative peaks. In some embodiments, a haptic stimulation is felt (or a greatest stimulation is felt) by a user at a location where constructive interference of waves occurs (i.e., at the target location). Thus, to create an intense haptic stimulation, a greater number of transducers may be activated, whereby more waves "add together." It is noted that a user may also feel the waves travelling through the medium to the target location; however, these haptic stimulations will be less noticeable relative to the haptic stimulation created and felt at the target location (i.e., where waves "add together").

As one example, two transducers of the wearable device **102** can produce waves (i.e., vibrations) that have respective frequencies of, say, 10,000,000 and 10,000,010 Hz. In such a circumstance, the user would feel 10 Hz (i.e., would feel the beat frequency) even though the produced waves have respective frequencies of 10,000,000 and 10,000,010 Hz. In another example, if a single transducer produces a wave with a frequency of 10,000,000 Hz, but the amplitude of the wave is modulated at 10 Hz (e.g., amplitude modulation, AM), the user will feel the 10 Hz. Using this concept, multiple waves modulated at 10 Hz can be focused (i.e., constructively interfere) at a target location by using multiple transducers with waves out of phase, or by having the AM from the transducers out of phase.

The discussion below further explains the "crawling waves." It is also noted that any number of transducers may be activated depending on the circumstance.

Oscillations or vibrations travel along (e.g., within) the wearer's body as a result of a wave **116** being generated by a transducer **410**. The resulting oscillations or vibrations from the wave **116** are sometimes referred to herein as crawling waves (the "crawling wave phenomena"). In the present context, the crawling wave phenomena refers to two or more sources (i.e., transducers) with different harmonic/acoustic (or the same) excitations that induce moving interference patterns in the wearer's body. A crawling wave generated by a transducer moves through the wearer's body with a phase velocity (v) that depends on the harmonic frequencies (f1, f2), and the shear wave speed (s). In some embodiments, the following equation represents the phase velocity (v) of a crawling wave:

$$v=s(f1-f2)\sqrt{4f1*f2}$$

As an example, when f1=500 Hz, f2=501 Hz, s=5 m/s, a phase velocity of v≈1 cm/s results. In some embodiments, values for the parameters of the equation above are provided by the computer system **130**, or the values are calculated by the wearable device **600** based on an instruction from the computer system **130**.

An example of multiple crawling waves constructively interfering with one another is illustrated in FIG. **12**. As shown, the crawling waves constructively interfere at location **1202**, which corresponds to a haptic stimulation. In some embodiments, time reversal focusing techniques are used to determine parameters of the crawling waves illustrated in FIG. **12**, as explained below. For example, the determined parameters are used to create the haptic stimulation at location **1202** (FIG. **12**).

In some embodiments, the transducers **410** focus ultrasound waves into the user using time reversal signal processing. In other words, the wearable device is a device that can focus waves using a time reversal method. Time reversal signal processing takes advantage of wave reciprocity, which is not altered by non-linear media, such as the user's skin. To focus the ultrasound waves using time reversal techniques, for each of the transducers **410**, the wearable device activates the respective transducers (e.g., each transducer shown in FIG. **12**) with a test signal and measures the response at the respective target location (e.g., location **1202**, FIG. **12**). Various instruments can be used to measure the response at the respective target location, including but not limited to a laser Doppler vibrometer. Thereafter, the measured signals are time-reversed. By activating the transducers **410** (e.g., all or less than all) with time-reversed versions of the measured signals, an excited skin (or other media) response can be created at the target location (e.g., the signals constructively interfere at the target location). As one skilled in the art will appreciate, in some instances, the parameters of each crawling wave are the same, whereas in some other instances, the parameters of crawling waves differs. Moreover, a first transducer may be activated at a first time and a second transducer may be activated at a second time (e.g., after the first time) (or in some embodiments, each transducer is activated simultaneously).

The discussion below with reference to FIGS. **9**C-**9**E describes a process for creating haptic stimulations on a user of the wearable device (e.g., waves **116** create stimulations felt at or near the wearable device's area of contact).

FIG. **9**C is a cross-sectional view **920** of the wearable device **600** taken along "A" view (FIG. **8**), in accordance with some embodiments. The user's arm has been removed from FIG. **9**C for ease of illustration. As shown, two transducers **410**A, **410**B are activated (indicated by shading), and each is generating a respective wave **116***a*, **116***b* (shown coming out of the page). In some embodiments, the wearable device **600** selectively activates a subset (e.g., two shaded transducers **410**A and **410**B) of the transducer array **110** based on an instruction received from the remote device **130** (FIG. **1**). In response to being activated, the two transducers **410**A and **410**B each generates a wave **116***a*, **116***b* that parallels the user's arm **802** and hand **804**. In doing so, a haptic sensation is created (e.g., a pull stimulation is felt at the user's wrist, or some other stimulation).

FIG. **9**D is an example top view **930** that shows the wearable device **600** and the user's arm taken along "B" view (FIG. **8**), in accordance with some embodiments. As shown, the two waves **116***a*, **116***b* generated by the two transducers **410**A, **410**B parallel the user's arm and hand. Values for characteristics of each wave are selected by the wearable device **600** (or the computer system **130**) so that the two waves **116***a*, **116***b* create a haptic stimulation corresponding to visual data displayed by the computer system **130** (e.g., a pull stimulation).

The pull stimulation illustrated in FIGS. **9**C-**9**D is merely one of the many possible haptic stimulations. For example, a touch stimulation, a swipe stimulation, a push stimulation (e.g., waves are generated in the opposite direction to the direction shown in FIGS. **9**C-**9**D), a rotation stimulation, among others, can also be created. Moreover, any number of transducers may be activated depending on the circumstance.

FIG. **9**E is a cross-sectional view **940** of the wearable device **600** taken along "A" view (FIG. **8**), in accordance with some embodiments. The user's arm has been removed from FIG. **9**E for ease of illustration. As shown, five transducers **410**A-**410**E are activated (indicated by shading), and each is generating a respective wave (or waves) indicated by arrows (note that the wave(s) for transducers **410**A and **410**B are coming out of the page and also potentially going into the page). Accordingly, the wearable device **600** is configured such that a first group of transducers can generate waves that travel in a first direction (e.g., into and/or out of the page), a second group of transducers can generate waves that travel in a second direction (e.g., east and/or west), and so on. It is noted that other directions not shown in FIGS. **9**A-**9**E are also possible such as 45 degrees, or various other angles with respect to the X, Y, or Z axes. Moreover, in some embodiments, the first group of transducers generates waves at a first time, the second group of transducers generates waves a second time, and so on. In doing so, the wearable device **600** is able to create various unique stimulations (e.g., a rotation stimulation). Alternatively, in some embodiments, each transducer generates waves simultaneously.

In some embodiments, the transducers **410** are arranged in multiple row and/or columns on the wearable device and transducers in a first respective column (or row) are adjacent to and parallel with corresponding transducers in a second respective column (or row) (e.g., transducers arrangement shown in FIG. **7**B). In such an arrangement, in some embodiments, adjacent transducers may generate waves that travel in the same direction (e.g., transducer **410**A and transducer **410**B in FIG. **7**B generates waves that travel to the right, or some other direction) or in different directions (e.g., transducer **410**A in FIG. **7**B generates one or more waves that travel to the right and transducer **410**B in FIG. **7**B generates one or more waves that travel to the left, or some other direction combination). It is noted that, in some embodiments, the wearable device may have a triple arrangement of transducers, a quadruple arrangement of transducers, and so on.

FIG. **10** is a flow diagram illustrating a method **1000** of generating haptic stimulations and topographic information in accordance with some embodiments. The steps of the method **1000** may be performed by a wearable device (e.g., a wearable device **102**, FIG. **1**). FIG. **10** corresponds to instructions stored in a computer memory or computer readable storage medium (e.g., memory **106** of the wearable device **102**). For example, the operations of method **1000** are performed, at least in part, by a communication module (e.g., communication module **218**, FIG. **2**), a sensor module (e.g., sensor module **220**, FIG. **2**), and/or a wave generating module (e.g., wave generating module **222**, FIG. **2**).

The method **1000** is performed at a wearable device that includes a plurality of transducers (e.g., transducers **410**, FIG. **4**), where each transducer can generate one or more waves (e.g., waves **116**, FIG. **1**) (**1102**). In some embodiments, the transducers are piezoelectric devices (e.g., miniature piezoelectric ultrasonic transducers), single or multipole voice coil motors, or the like. In some embodiments, the one or more waves are mechanical waves (e.g., ultrasonic waves, soundwaves, etc.), electromagnetic waves, and/or various other waves. In some embodiments, a medium for the waves is the user's body (skin, flesh, bone, etc.). For example, the wearable device may be attached to a wrist of the user, and the one or more waves may propagate away from the wearable device through the user's body below the wearable device. Alternatively or in addition, in some embodiments, the medium is air.

In some embodiments, the wearable device further includes a band (e.g., wearable structure **402**, FIG. **4**; wearable structure **602**, FIG. **6**A) to be secured around a wrist (or other body part) of the user, and each of the plurality of transducers is coupled to (e.g., integrated with) the band. In some embodiments, transducers of the plurality are radially spaced along a perimeter of the band (e.g., transducer arrangement shown in FIG. **6**B). In some embodiments, the wearable device includes a housing that houses the components of the wearable device. Further, in some embodiments, the plurality of transducers contacts the user's skin (or is separated from the user's skin by a conductive agent **502**).

The method **1000** includes activating (**1004**) one or more first transducers of the plurality of transducers (e.g., transducers **410**A and **410**B, FIG. **9**A) based on an instruction. In some embodiments, the instruction is received from a remote device (e.g., computer system **130**, FIG. **1**). In some embodiments, activating the one or more first transducers includes activating the one or more first transducers simultaneously. Alternatively, in some embodiments, activating the one or more first transducers includes: (i) activating a first transducer (or a first group of transducers) of the one or more first transducers at a first time and (ii) activating a second transducer (or a second group of transducers) of the one or more first transducers at a second time after the first time. For example, in some circumstances (e.g., depending on a target location and a position of each transducer on the wearable device), two or more of the first transducers are activated at different times to ensure that the waves transmitted by the two or more first transducers constructively interfere with another at the target location. In some embodiments, the instruction includes a time difference between each respective activation.

In some embodiments, the method **1000** further includes selecting values for characteristics of waves to be generated by the one or more first transducers based, at least in part, on a known impedance of the medium (e.g., using known impedances information **232**, FIG. **2**). In some instances, the known impedance of the medium is determined based on characteristics of the user. The characteristics of the user include but are not limited to age, sex, body fat index, and area of the body. The characteristics of the waves include but are not limited to frequency, amplitude, phase, wavelength, pulse duration, and gain. Shapes of the waves include but are not limited to sine, triangle, square, asymmetric, and arbitrary.

Waves generated by the activated one or more first transducers provide a haptic stimulation to the user of the wearable device. In some embodiments, the haptic stimulation corresponds to visual data displayed by the remote device (e.g., visual data displayed by the head-mounted display **140**, FIG. **1**). In order to maintain a sense of realism, the haptic stimulation must coincide with the corresponding visual data. To accomplish this, the instruction from the remote device may include a time delay, and activating the one or more first transducers is then performed in accordance with the time delay. Other techniques known by those skilled in the art can also be employed to ensure that the haptic stimulation coincides with the corresponding visual data. The haptic stimulation may also correspond to information received from one or more sensors of the wearable device **102** (e.g., based on information from the optional IMU and/or information from the sensors **114**, such as a heart rate sensor). Further, the haptic stimulation may also correspond to information received from one or more sensors of the head-mounted display.

The method **1000** further includes activating (**1006**) one or more second transducers of the plurality of transducers. In some embodiments, activating the one or more second transducers includes activating the one or more second transducers simultaneously. Alternatively, in some embodiments, activating the one or more second transducers includes: (i) activating a first transducer (or a first group of transducers) of the one or more second transducers at a first time and (ii) activating a second transducer (or a second group of transducers) of the one or more second transducers at a second time after the first time. In some embodiments, the instruction includes a time difference between each respective activation.

In some embodiments, activating the one or more second transducers is performed in response to receiving the instruction. In some embodiments, activating the one or more second transducers is performed periodically during use (e.g., every second, or some lesser or greater time period).

Waves (signals) generated by the activated one or more second transducers provide anatomical information of a user of the wearable device when the waves are received by one or more transducers of the plurality of transducers. In some embodiments, the anatomical information corresponds to a user's hand posture at a particular point in time (e.g., when the wearable device is attached to the user's wrist as shown in FIGS. **5**A-**5**B). In some embodiments, the one or more transducers of the plurality of transducers that receive the waves are opposite the one or more second transducers (e.g., as shown in FIG. **5**B). In some embodiments, the one or more transducers that receive the waves generated by the activated one or more second transducers include one or more transducers from (i) the one or more second transducers and/or (ii) the one or more first transducers. In some embodiments, the one or more transducers that receive the waves generated by the activated one or more second transducers are not part of the one or more second transducers or the one or more first transducers. Determining a hand posture of the user is discussed in further detail above with reference to FIGS. **5**A-**5**C.

In some embodiments, activating the one or more first transducers and the one or more second transducers includes simultaneously activating the first and second transducers. Alternatively, in some embodiments, the one or more first transducers are activated at a first time and the one or more second transducers are activated a second time different from the first time (e.g., the one or more second transducers may be activated before the one or more first transducers).

In some embodiments, the waves generated by the one or more first transducers are generated at a first frequency within a first frequency range, the waves generated by the one or more second transducers are generated at a second frequency within a second frequency range different from the first frequency range. For example, the first frequency range may range from about 20 Hz to 1000 Hz and the second frequency range may range from about 10 kHz to 60 kHz. The waves generated by the one or more first transducers may have the same frequencies or different frequencies within the first frequency range.

The waves generated by the one or more second transducers may have the same frequencies or different frequencies within the second frequency range. In some instances, different frequencies are needed to acquire comprehensive anatomical information for a particular portion of the body. For example, a first frequency may be used to obtain anatomical information for tendons whereas a second frequency may be used to obtain anatomical information for muscles (or some other body part). To illustrate, the wearable device may activate a first group of transducers, where the first group of transducers generates waves at a first frequency to gather first anatomical information. Subsequently (or simultaneously), the wearable device may activate a second group of transducers, where the second group of transducers generates waves at a second frequency to gather second anatomical information. The first and second groups may be the same or may differ in some respect. In some embodiments, the first and second anatomical information may compose the anatomical information.

In some embodiments, the wearable device includes a radio (e.g., communications component **112**, FIG. **1**) in wireless communication with the remote device (e.g., in wireless communication with communications component **136**, FIG. **1**). Further, in some embodiments, the method **1000** further includes receiving, via the radio, the instruction from the remote device (e.g., via a communication signal **118**, FIG. **1**).

Moreover, in some embodiments, the method **1000** further includes sending, via the radio, the anatomical information to the remote device after activating the one or more second transducers. In some embodiments, the anatomical information, when received by the remote device, causes the remote device to (i) generate at least a partial representation of the user of the wearable device from the anatomical information and (ii) include the representation in the visual data displayed by the head-mounted display. For example, when the wearable device is attached to the user's wrist, the remote device generates a representation of the user's hand (i.e., the partial representation of the user) from the anatomical information, thereby obtaining a posture of the user's hand. Further, the remote device includes the representation of the user's hand in the visual data, which is then displayed by the head-mounted display (e.g., a virtual hand is displayed having the posture of the user's hand).

In some instances, the generated representation of the user's hand can be further used to identity a gesture being made by the user. For example, the representation of the user's hand may indicate that the user is making a pinch gesture with his right hand. In another example, the representation of the user's hand may indicate that the user is pressing (or attempting to press on) on a surface with one finger (or multiple fingers). In yet another example, the representation of the user's hand may indicate that the user is making a full-hand swipe gesture or a finger swipe gesture (e.g., to swipe through virtual or augmented objects, or dismiss a virtual object or menu). In yet another example, the representation of the user's hand may indicate that the user is attempting to grasp an object. Various other gestures could also be detected and used to manipulate what is displayed by the head-mounted display.

In some embodiments, the instruction is based at least in part on the anatomical information generated by the wearable device. For example, a location (or some other characteristic) of the haptic stimulation in the instruction may correspond to the partial representation of the user generated by the remote device. Moreover, the remote device may change one or more characteristics of the wave(s) generated by the one or more first transducers and/or may change the transducers that might have otherwise been activated (e.g., adjust values of the characteristics of the wave(s)). In these embodiments, the one or more second transducers are activated before the one or more first transducers.

In some embodiments, the remote device combines the anatomical information with other forms of data to generate the partial representation of the user. For example, the anatomical information may be combined with image data captured by the one or more cameras **139** of the remote device, and the remote device generates the partial representation of the user using the anatomical information and the image data. In another example (in addition to or separate from the previous example), the anatomical information may be combined with IMU data captured by an IMU of the wearable device (e.g., the wearable device sends the IMU data to the remote device **130**). Moreover, at least in some embodiments, the remote device combines anatomical information, image data, and IMU data to generate the partial representation of the user. In some embodiments, the processors **132** of the remote device **130** and/or the processors **141** of the head-mounted display generate the partial representation of the user.

In some embodiments, the one or more first transducers (and/or the one or more second transducers) are separated from one another by at least one other transducer. Alternatively, in some embodiments, the one or more first transducers (and/or the one or more second transducers) are adjacent to one another on the wearable device. In some embodiments, transducers of the plurality are spaced equidistant from one another on the wearable device. In some embodiments, the one or more first transducers and the one or more second transducers are the same transducers. Further, in some embodiments, the one or more first transducers and the one or more second transducers include all the transducers in the plurality of transducers.

In some embodiments, the wearable device is a first wearable device (e.g., the first wearable device is attached to a left wrist of the user). Further, one or more additional wearable devices (e.g., **102***b*, **102***c*, etc.) may be attached to various other parts of the user (e.g., the right wrist of the user, an ankle of the user, a bicep of the user, and so on). Each additional wearable device is configured to perform the steps of method **1000**. For example, the wearable device attached to a right bicep of the user can be used to determine whether the user's arm is straight or flexed by obtaining anatomical information of the right bicep. Moreover, the wearable device attached to the right bicep could also create one or more haptic stimulations along the right bicep based on an instruction from the remote device.

In some embodiments, the remote device uses mapping data **334** (FIG. **3**) to track a location of each wearable device. For example, the wearable device **102** is not limited to particular appendage, and therefore, the remote device updates the mapping data **334** periodically (e.g., at start-up of the system). To accomplish the updating, the wearable device(s) being used each send location information to the remote device (e.g., using a location detection device, discussed with reference to FIG. **2**), and the remote device updates the mapping data **334** based on the location information. In this way, the remote device can determine that a first wearable device is attached to the user's left arm, even though the first wearable device was attached to the right arm during a previous use. In some embodiments, each wearable device has a unique identifier that allows the remote device to differentiate between each wearable device (as described above with reference to FIG. **2**). The identifier may be included in the location information or may be sent separately.

FIG. **11** is a flow diagram illustrating a method **1100** of managing creation of haptic stimulations and anatomical information in accordance with some embodiments. The steps of the method **1100** may be performed by a remote device (e.g., computer system **130**, FIG. **1**) (**1102**). FIG. **11** corresponds to instructions stored in a computer memory or computer readable storage medium (e.g., memory **134** of the computer system **130**). For example, the operations of method **1100** are performed, at least in part, by a communication module (e.g., communication module **318**, FIG. **3**), a virtual-reality/augment reality generation module (e.g., virtual-reality generation module **320**, FIG. **3**), an instruction generation module (e.g., instruction generation module **322**, FIG. **3**), and/or a display module (e.g., display module **324**, FIG. **3**). It is noted that the steps of the method **1100** can be performed in conjunction with the steps the method **1000**. In some embodiments, the host system corresponds to the AR system **1400** and/or the VR system **1500**.

The method **1100** includes generating (**1104**) an instruction that corresponds to visual data to be displayed by the remote device (and/or corresponds to information received from one or more sensors of the wearable device **102**). In some embodiments, the remote device generates the instruction based on information received from the sensors **114** on the wearable device **102**. Additionally, the information received by the remote device can also include information from the head-mounted display **140**. For example, cameras on the head-mounted display **140** may capture movements of the wearable device **102**, and the remote device can use this additional information when generating the instruction.

The method **1100** further includes sending (**1106**) the instruction to the wearable device in communication with the remote device (e.g., send the instruction in a communication signal **118** from the communications component **136**, FIG. **1**). The instruction, when received by the wearable device, causes the wearable device to activate one or more first transducers included in the wearable device (as explained above at step **1004** (FIG. **10**). Further, in some embodiments, the instruction, when received by the wearable device, causes the wearable device to activate one or more second transducers included in the wearable device (e.g., step **1006**, FIG. **10**). As discussed above with reference to step **1006**, waves generated by the activated one or more second transducers provide anatomical information of a user of the wearable device when the waves are received by one or more transducers of the plurality of transducers.

After (or while) sending the instruction, the method **1100** further includes displaying (**1108**) the visual data. For example, the head-mounted display **140** may receive the visual data from the remote device, and may in turn display the visual data on the display **144**. As an example, if the remote device receives information from the sensors **114** of the wearable device **102** that the user has closed his fingers around a position corresponding to a coffee mug in the virtual environment and raised his hand, a simulated hand in a virtual-reality application (e.g., VR application **336**, FIG. **3**) picks up the virtual coffee mug and lifts it to a corresponding height.

In conjunction with displaying the visual data, the wearable device activates one or more first transducers of the plurality of transducers based on the instruction received from the remote device. Waves generated by the activated one or more first transducers provide a haptic stimulation on a user of the wearable device, where the haptic stimulation created on the user corresponds to the visual data displayed by the remote device (described in more detail above with reference to the method **1000**). For example, using the coffee cup example from above, the haptic stimulation may prevent one or more of the user's finger from curling past a certain point to simulate the sensation of touching a solid coffee mug.

In some embodiments, the method **1100** further includes receiving (e.g., via communications component **136**, FIG. **1**) anatomical information from the wearable device. For example, the anatomical information corresponds to a user's hand posture at a particular point in time. In response to receiving the anatomical information, the method **1100** further includes generating at least a partial representation of the user of the wearable device from the anatomical information (described in more detail above with reference to the method **1000**).

To further illustrate, additional examples are provided below.

The remote device may communicate visual data with a head-mounted display **140** (FIG. **1**), where the visual data, when displayed by the head-mounted display, depicts the wearer's character in a virtual-reality (or augmented-reality) video game holding a bow and arrow. Prior to displaying release of the arrow, the remote device also communicates an instruction to a wearable device, where the instruction, when performed by the wearable device, causes the wearable device to activate one or more transducers that, when activated, create a haptic stimulation on the user that mimics the arrow being released from the bow displayed by the head-mounted display **140**.

In addition (still with reference to the bow and arrow example), the wearable device may generate anatomical information that corresponds to the user's hand holding the frame of the bow (another wearable device could also generate anatomical information that corresponds to the user's other hand holding the string of the bow). The wearable device may in turn send the anatomical information to the remote device (in some embodiments, the anatomical information is sent to the remote device before the head-mounted display displays the user's hand(s)). The anatomical information, when received by the remote device, causes the remote device to generate (or modify) a representation of the user's hand holding the frame of the bow (e.g., the remote device processes the anatomical information and generates the representation based on the anatomical information). Thereafter, the remote device can incorporate the representation into the visual data to be displayed by the head-mounted display. In doing so, the hand displayed by the head-mounted display mimics the actual pose of the user's hand.

Moreover (still with reference to the bow and arrow example), in some embodiments, the instruction is based at least in part on the generated representation (i.e., the anatomical information), as described above with reference to the method **1000**. To illustrate using the bow and arrow example, assume prior to receiving and processing the anatomical information, the instruction would have instructed the wearable device to create a haptic stimulation along the user's index finger. However, after receiving and processing the anatomical information, the remote device modifies the instruction, where the modified instruction instructs the wearable device to create a haptic stimulation along the user's middle finger (or some other body part).

It is noted that multiple haptic stimulations can be created to follow along with the video data displayed by the head-mounted display **140**. For example, a first haptic stimulation may be created at a first time, a second haptic stimulation may be created at a second time, and so on. Moreover, if multiple wearable devices are in communication with the remote device, then multiple haptic stimulations can be created at different locations on the user's body. For example, a first haptic stimulation may be created at a first limb by a first wearable device, a second haptic stimulation may be created at a second limb by a second wearable device, and so on.

Additionally, multiple versions of anatomical information can be created to continually update the visual data displayed by the head-mounted display **140**. For example, first anatomical information may be created at a first time, second anatomical information may be created at a second time, and so on. Moreover, if multiple wearable devices are in communication with the remote device, then different anatomical information can be created at different locations on the user's body. It is further noted that in some instances the anatomical information may be gathered prior to visual data being displayed by the head-mounted display. For example, the wearable device may continuously gather anatomical information that corresponds to the user's hand pose (or some other body part depending on a location of the wearable device). In this way, the remote device may also continuously update the visual data to account for changes in the user's hand pose.

Embodiments of the instant disclosure may include or be implemented in conjunction with various types of artificial reality systems. Artificial reality may constitute a form of reality that has been altered by virtual objects for presentation to a user. Such artificial reality may include and/or represent VR, AR, MR, hybrid reality, or some combination and/or variation of one or more of the same. Artificial reality content may include completely generated content or generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, haptic feedback, or some combination thereof, any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional effect to a viewer). Additionally, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, e.g., create content in an artificial reality and/or are otherwise used in (e.g., to perform activities in) an artificial reality.

Artificial reality systems may be implemented in a variety of different form factors and configurations. Some artificial reality systems may be designed to work without near-eye displays (NEDs), an example of which is AR system **1300** in FIG. **13**. Other artificial reality systems may include an NED that also provides visibility into the real world (e.g., AR system **1400** in FIG. **14**) or that visually immerses a user in an artificial reality (e.g., VR system **1500** in FIG. **15**). While some artificial reality devices may be self-contained systems, other artificial reality devices may communicate and/or coordinate with external devices to provide an artificial reality experience to a user. Examples of such external devices include handheld controllers, mobile devices, desktop computers, devices worn by a user (e.g., wearable device **102***a*, wearable device **102***b*, . . . wearable device **102***n*), devices worn by one or more other users, and/or any other suitable external system.

FIGS. **13-15** provide additional examples of the devices used in the system **100**. AR system **1300** in FIG. **13** generally represents a wearable device dimensioned to fit about a body part (e.g., a head) of a user. The AR system **1300** may include the functionality of the wearable device **102**, and may include additional functions. As shown, the AR system **1300** includes a frame **1302** (e.g., band) and a camera assembly **1304** that is coupled to frame **1302** and configured to gather information about a local environment by observing the local environment. The AR system **1300** may also include one or more transducers (e.g., instances of the transducers **410**, FIG. **4**). In one example, the AR system **1300** includes output transducers **1308**(A) and **1308**(B) and input transducers **1310**. Output transducers **1308**(A) and **1308**(B) may provide audio feedback, haptic feedback, and/or content to a user, and input audio transducers may capture audio (or other signals/waves) in a user's environment. As such, the transducers of the AR system **1300** may be configured to generate waves for creating haptic stimulations, as discussed in detail above.

Thus, the AR system **1300** does not include a near-eye display (NED) positioned in front of a user's eyes. AR systems without NEDs may take a variety of forms, such as head bands, hats, hair bands, belts, watches, wrist bands, ankle bands, rings, neckbands, necklaces, chest bands, eyewear frames, and/or any other suitable type or form of apparatus. While the AR system **1300** may not include an NED, the AR system **1300** may include other types of screens or visual feedback devices (e.g., a display screen integrated into a side of frame **1302**).

The embodiments discussed in this disclosure may also be implemented in AR systems that include one or more NEDs. For example, as shown in FIG. **14**, the AR system **1400** may include an eyewear device **1402** with a frame **1410** configured to hold a left display device **1415**(A) and a right display device **1415**(B) in front of a user's eyes. Display devices **1415**(A) and **1415**(B) may act together or independently to present an image or series of images to a user. While the AR system **1400** includes two displays, embodiments of this disclosure may be implemented in AR systems with a single NED or more than two NEDs.

In some embodiments, the AR system **1400** may include one or more sensors, such as sensor **1440**. Sensor **1440** may generate measurement signals in response to motion of AR system **1400** and may be located on substantially any portion of frame **1410**. Sensor **1440** may include a position sensor, an inertial measurement unit (IMU), a depth camera assembly, or any combination thereof. In some embodiments, the AR system **1400** may or may not include sensor **1440** or may include more than one sensor. In embodiments in which sensor **1440** includes an IMU, the IMU may generate calibration data based on measurement signals from sensor **1440**. Examples of sensor **1440** may include, without limitation, accelerometers, gyroscopes, magnetometers, other suitable types of sensors that detect motion, sensors used for error correction of the IMU, or some combination thereof. Sensors are also discussed above with reference to FIG. **1** (e.g., sensors **145** of the head-mounted display **140**).

The AR system **1400** may also include a microphone array with a plurality of acoustic sensors **1420**(A)-**1420**(J), referred to collectively as acoustic sensors **1420**. Acoustic sensors **1420** may be transducers that detect air pressure variations induced by sound waves. Each acoustic sensor **1420** may be configured to detect sound and convert the detected sound into an electronic format (e.g., an analog or digital format). The microphone array in FIG. **14** may include, for example, ten acoustic sensors: **1420**(A) and **1420**(B), which may be designed to be placed inside a corresponding ear of the user, acoustic sensors **1420**(C), **1420**(D), **1420**(E), **1420**(F), **1420**(G), and **1420**(H), which may be positioned at various locations on frame **1410**, and/or acoustic sensors **1420**(I) and **1420**(J), which may be positioned on a corresponding neckband **1405**. In some embodiments, the neckband **1405** is an example of the computer system **130**.

The configuration of acoustic sensors **1420** of the microphone array may vary. While the AR system **1400** is shown in FIG. **14** as having ten acoustic sensors **1420**, the number of acoustic sensors **1420** may be greater or less than ten. In some embodiments, using higher numbers of acoustic sensors **1420** may increase the amount of audio information collected and/or the sensitivity and accuracy of the audio information. In contrast, using a lower number of acoustic sensors **1420** may decrease the computing power required by a controller **1450** to process the collected audio information. In addition, the position of each acoustic sensor **1420** of the microphone array may vary. For example, the position of an acoustic sensor **1420** may include a defined position on the user, a defined coordinate on the frame **1410**, an orientation associated with each acoustic sensor, or some combination thereof.

Acoustic sensors **1420**(A) and **1420**(B) may be positioned on different parts of the user's ear, such as behind the pinna or within the auricle or fossa. Or, there may be additional acoustic sensors on or surrounding the ear in addition to acoustic sensors **1420** inside the ear canal. Having an acoustic sensor positioned next to an ear canal of a user may enable the microphone array to collect information on how sounds arrive at the ear canal. By positioning at least two of acoustic sensors **1420** on either side of a user's head (e.g., as binaural microphones), the AR device **1400** may simulate binaural hearing and capture a 3D stereo sound field around about a user's head. In some embodiments, the acoustic sensors **1420**(A) and **1420**(B) may be connected to the AR system **1400** via a wired connection, and in other embodiments, the acoustic sensors **1420**(A) and **1420**(B) may be connected to the AR system **1400** via a wireless connection (e.g., a Bluetooth connection). In still other embodiments, acoustic sensors **1420**(A) and **1420**(B) may not be used at all in conjunction with the AR system **1400**.

Acoustic sensors **1420** on frame **1410** may be positioned along the length of the temples, across the bridge, above or below display devices **1415**(A) and **1415**(B), or some combination thereof. Acoustic sensors **1420** may be oriented such that the microphone array is able to detect sounds in a wide range of directions surrounding the user wearing AR system **1400**. In some embodiments, an optimization process may be performed during manufacturing of AR system **1400** to determine relative positioning of each acoustic sensor **1420** in the microphone array.

The AR system **1400** may further include or be connected to an external device (e.g., a paired device), such as neckband **1405**. As shown, neckband **1405** may be coupled to eyewear device **1402** via one or more connectors **1430**. Connectors **1430** may be wired or wireless connectors and may include electrical and/or non-electrical (e.g., structural) components. In some cases, eyewear device **1402** and neckband **1405** may operate independently without any wired or wireless connection between them. While FIG. **14** illustrates the components of eyewear device **1402** and neckband **1405** in example locations on eyewear device **1402** and neckband **1405**, the components may be located elsewhere and/or distributed differently on eyewear device **1402** and/or neckband **1405**. In some embodiments, the components of eyewear device **1402** and neckband **1405** may be located on one or more additional peripheral devices paired with eyewear device **1402**, neckband **1405**, or some combination thereof. Furthermore, neckband **1405** generally represents any type or form of paired device. Thus, the following discussion of neckband **1405** may also apply to various other paired devices, such as smart watches, smart phones, wrist bands, other wearable devices, hand-held controllers, tablet computers, laptop computers, etc.

Pairing external devices, such as neckband **1405**, with AR eyewear devices may enable the eyewear devices to achieve the form factor of a pair of glasses while still providing sufficient battery and computation power for expanded capabilities. Some or all of the battery power, computational resources, and/or additional features of the AR system **1400** may be provided by a paired device or shared between a paired device and an eyewear device, thus reducing the weight, heat profile, and form factor of the eyewear device overall while still retaining desired functionality. For example, neckband **1405** may allow components that would otherwise be included on an eyewear device to be included in neckband **1405** since users may tolerate a heavier weight load on their shoulders than they would tolerate on their heads. Neckband **1405** may also have a larger surface area over which to diffuse and disperse heat to the ambient environment. Thus, neckband **1405** may allow for greater battery and computation capacity than might otherwise have been possible on a stand-alone eyewear device. Since weight carried in neckband **1405** may be less invasive to a user than weight carried in eyewear device **1402**, a user may tolerate wearing a lighter eyewear device and carrying or wearing the paired device for greater lengths of time than the user would tolerate wearing a heavy standalone eyewear device, thereby enabling an artificial reality environment to be incorporated more fully into a user's day-to-day activities.

Neckband **1405** may be communicatively coupled with eyewear device **1402** and/or to other devices. The other devices may provide certain functions (e.g., tracking, localizing, depth mapping, processing, storage, etc.) to the AR system **1400**. In the embodiment of FIG. **14**, neckband **1405** may include two acoustic sensors (e.g., **1420**(I) and **1420**(J)) that are part of the microphone array (or potentially form their own microphone subarray). Neckband **1405** may also include a controller **1425** and a power source **1435**.

Acoustic sensors **1420**(I) and **1420**(J) of neckband **1405** may be configured to detect sound and convert the detected sound into an electronic format (analog or digital). In the embodiment of FIG. **14**, acoustic sensors **1420**(I) and **1420**(J) may be positioned on neckband **1405**, thereby increasing the distance between neckband acoustic sensors **1420**(I) and **1420**(J) and other acoustic sensors **1420** positioned on eyewear device **1402**. In some cases, increasing the distance between acoustic sensors **1420** of the microphone array may improve the accuracy of beamforming performed via the microphone array. For example, if a sound is detected by acoustic sensors **1420**(C) and **1420**(D) and the distance between acoustic sensors **1420**(C) and **1420**(D) is greater than, e.g., the distance between acoustic sensors **1420**(D) and **1420**(E), the determined source location of the detected sound may be more accurate than if the sound had been detected by acoustic sensors **1420**(D) and **1420**(E).

Controller **1425** of neckband **1405** may process information generated by the sensors on neckband **1405** and/or AR system **1400**. For example, controller **1425** may process information from the microphone array that describes sounds detected by the microphone array. For each detected sound, controller **1425** may perform a direction of arrival (DOA) estimation to estimate a direction from which the detected sound arrived at the microphone array. As the microphone array detects sounds, controller **1425** may populate an audio data set with the information. In embodiments in which AR system **1400** includes an IMU, controller **1425** may compute all inertial and spatial calculations from the IMU located on eyewear device **1402**. Connector **1430** may convey information between AR system **1400** and neckband **1405** and between AR system **1400** and controller **1425**. The information may be in the form of optical data, electrical data, wireless data, or any other transmittable data form. Moving the processing of information generated by AR system **1400** to neckband **1405** may reduce weight and heat in eyewear device **1402**, making it more comfortable to a user.

Power source **1435** in neckband **1405** may provide power to eyewear device **1402** and/or to neckband **1405**. Power source **1435** may include, without limitation, lithium-ion batteries, lithium-polymer batteries, primary lithium batteries, alkaline batteries, or any other form of power storage. In some cases, power source **1435** may be a wired power source. Including power source **1435** on neckband **1405** instead of on eyewear device **1402** may help better distribute the weight and heat generated by power source **1435**.

As noted, some artificial reality systems may, instead of blending an artificial reality with actual reality, substantially replace one or more of a user's sensory perceptions of the real world with a virtual experience. One example of this type of system is a head-worn display system, such as VR system **1500** in FIG. **15**, that mostly or completely covers a user's field of view. VR system **1500** may include a front rigid body **1502** and a band **1504** shaped to fit around a user's head. VR system **1500** may also include output audio transducers **1506**(A) and **1506**(B). Furthermore, while not shown in FIG. **15**, front rigid body **1502** may include one or more electronic elements, including one or more electronic displays, one or more IMUs, one or more tracking emitters or detectors, and/or any other suitable device or system for creating an artificial reality experience. Although not shown, the VR system **1500** may include the computer system **130**.

Artificial reality systems may include a variety of types of visual feedback mechanisms. For example, display devices in AR system **1400** and/or VR system **1500** may include one or more liquid-crystal displays (LCDs), light emitting diode

(LED) displays, organic LED (OLED) displays, and/or any other suitable type of display screen. Artificial reality systems may include a single display screen for both eyes or may provide a display screen for each eye, which may allow for additional flexibility for varifocal adjustments or for correcting a user's refractive error. Some artificial reality systems may also include optical subsystems having one or more lenses (e.g., conventional concave or convex lenses, Fresnel lenses, adjustable liquid lenses, etc.) through which a user may view a display screen.

In addition to or instead of using display screens, some artificial reality systems may include one or more projection systems. For example, display devices in AR system **1400** and/or VR system **1500** may include micro-LED projectors that project light (using, e.g., a waveguide) into display devices, such as clear combiner lenses that allow ambient light to pass through. The display devices may refract the projected light toward a user's pupil and may enable a user to simultaneously view both artificial reality content and the real world. Artificial reality systems may also be configured with any other suitable type or form of image projection system.

Artificial reality systems may also include various types of computer vision components and subsystems. For example, AR system **1300**, AR system **1400**, and/or VR system **1500** may include one or more optical sensors such as two-dimensional (2D) or three-dimensional (3D) cameras, time-of-flight depth sensors, single-beam or sweeping laser rangefinders, 3D LiDAR sensors, and/or any other suitable type or form of optical sensor. An artificial reality system may process data from one or more of these sensors to identify a location of a user, to map the real world, to provide a user with context about real-world surroundings, and/or to perform a variety of other functions.

Artificial reality systems may also include one or more input and/or output audio transducers. In the examples shown in FIGS. **13** and **15**, output audio transducers **1308**(A), **1308**(B), **1306**(A), and **1506**(B) may include voice coil speakers, ribbon speakers, electrostatic speakers, piezoelectric speakers, bone conduction transducers, cartilage conduction transducers, and/or any other suitable type or form of audio transducer. Similarly, input audio transducers **1310** may include condenser microphones, dynamic microphones, ribbon microphones, and/or any other type or form of input transducer. In some embodiments, a single transducer may be used for both audio input and audio output.

The artificial reality systems shown in FIGS. **13**-**15** may include tactile (i.e., haptic) feedback systems, which may be incorporated into headwear, gloves, body suits, handheld controllers, environmental devices (e.g., chairs, floormats, etc.), and/or any other type of device or system, such as the wearable devices **102** discussed herein. Additionally, in some embodiments, the haptic feedback systems may be incorporated with the artificial reality systems (e.g., the AR system **1300** may include the wearable device **102** (FIG. **1**). Haptic feedback systems may provide various types of cutaneous feedback, including vibration, force, traction, texture, and/or temperature. Haptic feedback systems may also provide various types of kinesthetic feedback, such as motion and compliance. Haptic feedback may be implemented using motors, piezoelectric actuators, fluidic systems, and/or a variety of other types of feedback mechanisms. Haptic feedback systems may be implemented independent of other artificial reality devices, within other artificial reality devices, and/or in conjunction with other artificial reality devices.

By providing haptic sensations, audible content, and/or visual content, artificial reality systems may create an entire virtual experience or enhance a user's real-world experience in a variety of contexts and environments. For instance, artificial reality systems may assist or extend a user's perception, memory, or cognition within a particular environment. Some systems may enhance a user's interactions with other people in the real world or may enable more immersive interactions with other people in a virtual world. Artificial reality systems may also be used for educational purposes (e.g., for teaching or training in schools, hospitals, government organizations, military organizations, business enterprises, etc.), entertainment purposes (e.g., for playing video games, listening to music, watching video content, etc.), and/or for accessibility purposes (e.g., as hearing aids, vision aids, etc.). The embodiments disclosed herein may enable or enhance a user's artificial reality experience in one or more of these contexts and environments and/or in other contexts and environments.

Some AR systems may map a user's environment using techniques referred to as "simultaneous location and mapping" (SLAM). SLAM mapping and location identifying techniques may involve a variety of hardware and software tools that can create or update a map of an environment while simultaneously keeping track of a device's or a user's location and/or orientation within the mapped environment. SLAM may use many different types of sensors to create a map and determine a device's or a user's position within the map.

SLAM techniques may, for example, implement optical sensors to determine a device's or a user's location, position, or orientation. Radios including WiFi, Bluetooth, global positioning system (GPS), cellular or other communication devices may also be used to determine a user's location relative to a radio transceiver or group of transceivers (e.g., a WiFi router or group of GPS satellites). Acoustic sensors such as microphone arrays or 2D or 3D sonar sensors may also be used to determine a user's location within an environment. AR and VR devices (such as systems **1300**, **1400**, and **1500**) may incorporate any or all of these types of sensors to perform SLAM operations such as creating and continually updating maps of a device's or a user's current environment. In at least some of the embodiments described herein, SLAM data generated by these sensors may be referred to as "environmental data" and may indicate a device's or a user's current environment. This data may be stored in a local or remote data store (e.g., a cloud data store) and may be provided to a user's AR/VR device on demand.

When the user is wearing an AR headset or VR headset in a given environment, the user may be interacting with other users or other electronic devices that serve as audio sources. In some cases, it may be desirable to determine where the audio sources are located relative to the user and then present the audio sources to the user as if they were coming from the location of the audio source. The process of determining where the audio sources are located relative to the user may be referred to herein as "localization," and the process of rendering playback of the audio source signal to appear as if it is coming from a specific direction may be referred to herein as "spatialization."

Localizing an audio source may be performed in a variety of different ways. In some cases, an AR or VR headset may initiate a DOA analysis to determine the location of a sound source. The DOA analysis may include analyzing the intensity, spectra, and/or arrival time of each sound at the AR/VR device to determine the direction from which the sound originated. In some cases, the DOA analysis may include any suitable algorithm for analyzing the surrounding acoustic environment in which the artificial reality device is located.

For example, the DOA analysis may be designed to receive input signals from a microphone and apply digital signal processing algorithms to the input signals to estimate the direction of arrival. These algorithms may include, for example, delay and sum algorithms where the input signal is sampled, and the resulting weighted and delayed versions of the sampled signal are averaged together to determine a direction of arrival. A least mean squared (LMS) algorithm may also be implemented to create an adaptive filter. This adaptive filter may then be used to identify differences in signal intensity, for example, or differences in time of arrival. These differences may then be used to estimate the direction of arrival. In another embodiment, the DOA may be determined by converting the input signals into the frequency domain and selecting specific bins within the time-frequency (TF) domain to process. Each selected TF bin may be processed to determine whether that bin includes a portion of the audio spectrum with a direct-path audio signal. Those bins having a portion of the direct-path signal may then be analyzed to identify the angle at which a microphone array received the direct-path audio signal. The determined angle may then be used to identify the direction of arrival for the received input signal. Other algorithms not listed above may also be used alone or in combination with the above algorithms to determine DOA.

In some embodiments, different users may perceive the source of a sound as coming from slightly different locations. This may be the result of each user having a unique head-related transfer function (HRTF), which may be dictated by a user's anatomy including ear canal length and the positioning of the ear drum. The artificial reality device may provide an alignment and orientation guide, which the user may follow to customize the sound signal presented to the user based on their unique HRTF. In some embodiments, an AR or VR device may implement one or more microphones to listen to sounds within the user's environment. The AR or VR device may use a variety of different array transfer functions (ATFs) (e.g., any of the DOA algorithms identified above) to estimate the direction of arrival for the sounds. Once the direction of arrival has been determined, the artificial reality device may play back sounds to the user according to the user's unique HRTF. Accordingly, the DOA estimation generated using an ATF may be used to determine the direction from which the sounds are to be played from. The playback sounds may be further refined based on how that specific user hears sounds according to the HRTF.

In addition to or as an alternative to performing a DOA estimation, an artificial reality device may perform localization based on information received from other types of sensors. These sensors may include cameras, infrared radiation (IR) sensors, heat sensors, motion sensors, global positioning system (GPS) receivers, or in some cases, sensor that detect a user's eye movements. For example, an artificial reality device may include an eye tracker or gaze detector that determines where a user is looking. Often, a user's eyes will look at the source of a sound, if only briefly. Such clues provided by the user's eyes may further aid in determining the location of a sound source. Other sensors such as cameras, heat sensors, and IR sensors may also indicate the location of a user, the location of an electronic device, or the location of another sound source. Any or all of the above methods may be used individually or in combination to determine the location of a sound source and may further be used to update the location of a sound source over time.

Some embodiments may implement the determined DOA to generate a more customized output audio signal for the user. For instance, an acoustic transfer function may characterize or define how a sound is received from a given location. More specifically, an acoustic transfer function may define the relationship between parameters of a sound at its source location and the parameters by which the sound signal is detected (e.g., detected by a microphone array or detected by a user's ear). An artificial reality device may include one or more acoustic sensors that detect sounds within range of the device. A controller of the artificial reality device may estimate a DOA for the detected sounds (using, e.g., any of the methods identified above) and, based on the parameters of the detected sounds, may generate an acoustic transfer function that is specific to the location of the device. This customized acoustic transfer function may thus be used to generate a spatialized output audio signal where the sound is perceived as coming from a specific location.

Indeed, once the location of the sound source or sources is known, the artificial reality device may re-render (i.e., spatialize) the sound signals to sound as if coming from the direction of that sound source. The artificial reality device may apply filters or other digital signal processing that alter the intensity, spectra, or arrival time of the sound signal. The digital signal processing may be applied in such a way that the sound signal is perceived as originating from the determined location. The artificial reality device may amplify or subdue certain frequencies or change the time that the signal arrives at each ear. In some cases, the artificial reality device may create an acoustic transfer function that is specific to the location of the device and the detected direction of arrival of the sound signal. In some embodiments, the artificial reality device may re-render the source signal in a stereo device or multi-speaker device (e.g., a surround sound device). In such cases, separate and distinct audio signals may be sent to each speaker. Each of these audio signals may be altered according to a user's HRTF and according to measurements of the user's location and the location of the sound source to sound as if they are coming from the determined location of the sound source. Accordingly, in this manner, the artificial reality device (or speakers associated with the device) may re-render an audio signal to sound as if originating from a specific location.

Although some of various drawings illustrate a number of logical stages in a particular order, stages which are not order dependent may be reordered and other stages may be combined or broken out. While some reordering or other groupings are specifically mentioned, others will be obvious to those of ordinary skill in the art, so the ordering and groupings presented herein are not an exhaustive list of alternatives. Moreover, it should be recognized that the stages could be implemented in hardware, firmware, software or any combination thereof.

The foregoing description, for purpose of explanation, has been described with reference to specific embodiments. However, the illustrative discussions above are not intended to be exhaustive or to limit the scope of the claims to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. The embodiments were chosen in order to best explain the principles underlying the claims and their practical applications, to thereby enable others skilled in the art to best use the embodiments with various modifications as are suited to the particular uses contemplated.

It is noted that the embodiments disclosed herein can also be combined with any of the embodiments described in U.S.

Provisional Application No. 62/647,559, filed Mar. 23, 2018, entitled "Methods, Devices, and Systems for Determining Contact On a User of a Virtual Reality and/or Augmented Reality Device;" U.S. Provisional Application No. 62/647,560, filed Mar. 23, 2018, entitled "Methods, Devices, and Systems for Projecting an Image Onto a User and Detecting Touch Gestures"; and U.S. Provisional Application No. 62/614,790, filed Jan. 8, 2018, entitled "Methods, Devices, and Systems for Creating Localized Haptic Sensations on a User."

It also is noted that the embodiments disclosed herein can also be combined with any of the embodiments described in U.S. Utility patent application Ser. No. 16/241,890, entitled "Methods, Devices, and Systems for Determining Contact On a User of a Virtual Reality and/or Augmented Reality Device," filed Jan. 7, 2019, U.S. Utility patent application Ser. No. 16/241,893, entitled "Methods, Devices, and Systems for Displaying a User Interface on a User and Detecting Touch Gestures," filed Jan. 7, 2019, and U.S. Utility patent application Ser. No. 16/241,900, entitled "Methods, Devices, and Systems for Creating Localized Haptic Sensations on a User," filed Jan. 7, 2019.

What is claimed is:

1. A wearable device, comprising:

a plurality of transducers that can each generate one or more waves; and

one or more processors coupled with the plurality of transducers, the one or more processors being configured to:

activate one or more first transducers of the plurality of transducers based on a first instruction received from a remote device, wherein waves generated by the activated one or more first transducers provide a haptic stimulation to a user of the wearable device at a first target location;

activate one or more second transducers of the plurality of transducers, wherein waves generated by the activated one or more second transducers provide anatomical information of the user of the wearable device when the waves are received by one or more transducers of the plurality of transducers; and

in accordance with the anatomical information and a second instruction received from the remote device:

activate one or more third transducers of the plurality of transducers to provide a haptic stimulation to the user of the wearable device at a second target location distinct from the first target location.

2. The wearable device of claim **1**, wherein the instruction received from the remote device corresponds to visual data displayed by a head-mounted display in communication with the remote device.

3. The wearable device of claim **1**, further comprising a radio configured to receive the instruction from the remote device.

4. The wearable device of claim **1**, further comprising a radio configured to send the anatomical information to the remote device after activating the one or more second transducers.

5. The wearable device of claim **4**, wherein the anatomical information, when received by the remote device, causes the remote device to:

generate at least a partial representation of the user of the wearable device from the anatomical information; and

include the representation in visual data displayed by a head-mounted display in communication with the remote device.

6. The wearable device of claim **1**, wherein the anatomical information corresponds to a posture of the user's hand at a particular point in time.

7. The wearable device of claim **1**, wherein:

the waves generated by the one or more first transducers are generated at a first frequency within a first frequency range;

the waves generated by the one or more second transducers are generated at a second frequency within a second frequency range; and

the second frequency range is different from the first frequency range.

8. The wearable device of claim **1**, further comprising a band configured to be secured around a wrist or ankle of the user,

wherein each of the plurality of transducers is coupled to the band.

9. The wearable device of claim **8**, wherein transducers of the plurality of transducers are radially spaced along a perimeter of the band.

10. The wearable device of claim **9**, wherein the one or more transducers of the plurality of transducers that receive the waves are opposite the one or more second transducers on the band.

11. The wearable device of claim **1**, wherein transducers of the plurality of transducers are spaced equidistant from one another on the wearable device.

12. The wearable device of claim **1**, wherein:

transducers in the plurality of transducers are arranged in columns on the wearable device; and

transducers in a first respective column are adjacent to and parallel with corresponding transducers in a second respective column.

13. The wearable device of claim **1**, wherein the waves generated by the plurality of transducers are ultrasonic waves.

14. The wearable device of claim **1**, wherein the one or more processors are further configured to activate the one or more first transducers and the one or more second transducers simultaneously.

15. The wearable device of claim **1**, wherein the one or more processors are further configured to:

activate the one or more first transducers at a first time; and

activate the one or more second transducers at a second time different from the first time.

16. The wearable device of claim **1**, wherein the one or more transducers that receive the waves generated by the activated one or more second transducers include one or more transducers from (i) the one or more second transducers and/or (ii) the one or more first transducers.

17. The wearable device of claim **1**, wherein the one or more first transducers include:

a first group of transducers that generates waves in a first direction; and

a second group of transducers that generates waves in a second direction different from the first direction.

18. The wearable device of claim **1**, wherein the anatomical information is tomographic information.

19. A method, comprising:

at a wearable device comprising a plurality of transducers that can each generate one or more waves:

activating one or more first transducers of the plurality of transducers based on a first instruction received from a remote device, wherein waves generated by the activated one or more first transducers provide a haptic stimulation to a user of the wearable device at a first target location;

activating one or more second transducers of the plurality of transducers, wherein waves generated by the activated one or more second transducers provide anatomical information of the user of the wearable device when the waves are received by one or more transducers of the plurality of transducers; and

in accordance with the anatomical information and a second instruction received from the remote device:

activate one or more third transducers of the plurality of transducers to provide a haptic stimulation to the user of the wearable device at a second target location distinct from the first target location.

20. A non-transitory computer-readable storage medium, storing one or more programs configured for execution by one or more processors of a wearable device having a plurality of transducers, the one or more programs including instructions, which when executed by the one or more processors cause the wearable device to:

activate one or more first transducers of the plurality of transducers based on a first instruction received from a remote device, wherein waves generated by the activated one or more first transducers provide a haptic stimulation to a user of the wearable device at a first target location;

activate one or more second transducers of the plurality of transducers, wherein waves generated by the activated one or more second transducers provide anatomical information of the user of the wearable device when the waves are received by one or more transducers of the plurality of transducers; and

in accordance with the anatomical information and a second instruction received from the remote device:

activate one or more third transducers of the plurality of transducers to provide a haptic stimulation to the user of the wearable device at a second target location distinct from the first target location.

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